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# Neogene Extension and Regional Rotation of the Central Mojave Desert, California.

Timothy Michael Ross

*Louisiana State University and Agricultural & Mechanical College*

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Desert, California**

**Ross, Timothy Michael, Ph.D.**

**The Louisiana State University and Agricultural and Mechanical Col., 1994**

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Ann Arbor, MI 48106



**NEOGENE EXTENSION AND REGIONAL ROTATION OF THE  
CENTRAL MOJAVE DESERT, CALIFORNIA**

A Dissertation

Submitted to the Graduate Faculty of the  
Louisiana State University and  
Agricultural and Mechanical College  
in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy

in

The Department of Geology and Geophysics

by

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May 1994

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## ABSTRACT

The southwest Cady Mountains of San Bernardino County, California, contain key relationships which allow separation of the timing of early Miocene detachment-style extension and vertical-axis clockwise rotation in the Mojave Desert. The rock succession consists of a pre-Tertiary granitic basement overlain by three successive volcanic and volcanoclastic units of early to middle Miocene age referred to informally as the formation of Poe, the formation of Troy Peak and the "Barstow Formation". Deposition of the volcanic upper Oligocene/lower Miocene formation of Poe was accompanied by extension and tilting, facilitated by faults which do not cut the unconformably overlying formation of Troy Peak basalts. The rocks then experienced a clockwise rotation of  $63^{\circ} \pm 20^{\circ}$  prior to initiation of deposition of the "Barstow Fm." Following deposition of the mid-Miocene "Barstow Fm." ( $<14$  Ma), this area was folded into an antiform and rotated an additional  $67^{\circ} \pm 15^{\circ}$  clockwise. Upon removal of both clockwise rotations, the direction of early Miocene extension in the southwest Cady Mountains, indicated by geologic relationships, becomes aligned ~N-S.

The southwest Cady Mountains comprise a portion of the Daggett terrane of the Mojave extensional belt where all areas display similar orientation of extensional structures, except the southwest Cady Mountains. The removal of the post-14 Ma clockwise rotation from the southwest Cady Mountains brings the local direction of the early Miocene extension of the southwest Cady Mountains and the surrounding Daggett terrane into alignment. Other areas in and around the Mojave Desert block have also experienced early Miocene clockwise rotation. Upon removal of late Miocene to recent right-lateral strike-slip faulting, areas which have been affected by early Miocene clockwise rotation move into an approximate E-W alignment. This rotation can be explained by an early Miocene ~E-W directed right-lateral shear active prior to ~18.5 Ma. Removal of this right-lateral shear straightens structural bends in traces of pre-

Tertiary thrust systems, aligns a possible offset of the Independence dike swarm and removes clockwise rotations in and around the Mojave Desert block.

## **CHAPTER 1: GENERAL GEOLOGY OF THE MOJAVE DESERT AND INTRODUCTION TO THIS DISSERTATION**

### **INTRODUCTION**

The Neogene tectonic history of the Mojave Desert block (the area bounded by the San Andreas fault and the Garlock fault, extending eastward to  $\sim 116^{\circ}$  W longitude) has been an area of active study over the last decade (Figure 1.1). The two most widely recognized tectonic deformations to have affected this area during Neogene time are 1) early Miocene regional extension and 2) the presently active system of northwest-striking right-lateral shear. Both of these tectonic events have had much recent study, but another, less well understood regional tectonic event affected the Mojave Desert block; namely, a regional clockwise tectonic rotation which occurred during early Miocene time. This study establishes timing relationships, discusses the regional effects and presents a model and reconstruction of this newly recognized tectonic event.

### **GENERAL GEOLOGY OF THE MOJAVE DESERT**

Paleozoic and Mesozoic rocks and structures have been long recognized to crop out in the Mojave Desert. Amphibolite-grade metamorphic rocks which crop out mainly in the central and north-eastern portion of this area have been correlated with less metamorphosed Paleozoic age formations to the north and east of the Mojave (Stone and others, 1983; Walker and Wardlaw, 1989). Walker and his co-workers (Walker and others, 1990a,b; Martin and Walker, 1992) have developed the idea that Mesozoic and Paleozoic rocks, facies changes and deformational structures continue southward into the Mojave Desert. In particular, they suggest that a Mesozoic thrust system, the eastern California thrust system (ECTS), continues from the Death Valley area southward to the central Mojave Desert. Snow (1992; see also Stone and Stevens, 1993; Snow and

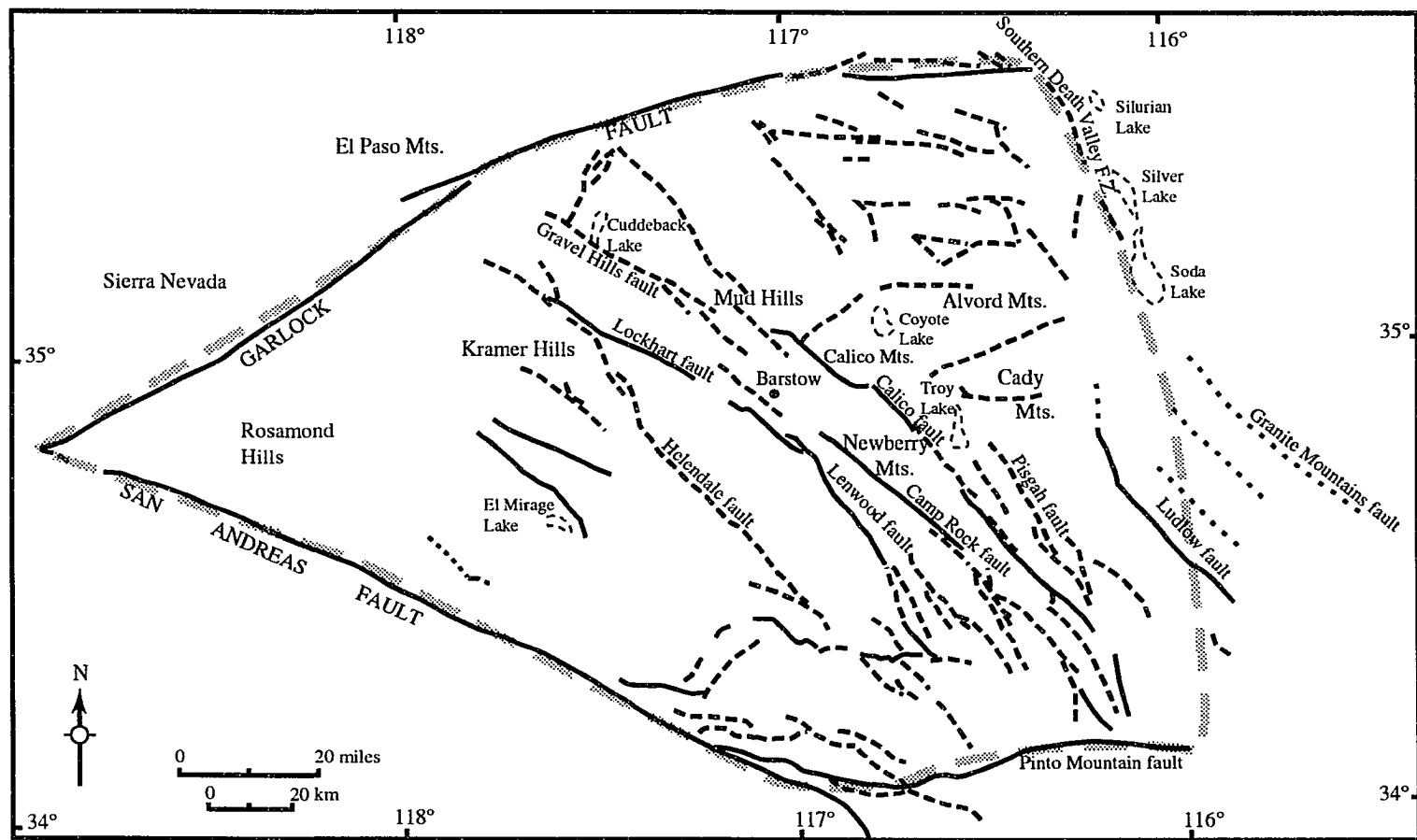


Figure 1.1 Location map for the Mojave Desert, California. Approximate boundaries of the Mojave Desert block (cf. Dokka, 1983) are shown in grey dashed line.

Wernicke, 1993) suggested that a Permian thrust system exposed north of the Garlock fault, the Last Chance thrust system (LCTS) also continues into the Mojave Desert block. In addition, the Jurassic Independence dike swarm was proposed to extend southward from the Sierra Nevada into the Mojave Desert (Smith, 1962) and continue southward through the central Mojave (James, 1989). These Mesozoic and older rocks and structures serve as markers with which to constrain younger deformation.

### **Early Miocene Regional Extension**

The Mojave Desert was the site of regional extension during early Miocene time. Dokka (1986, 1989ab) separated this extensional belt into domains of extension with each domain separated from its neighbors by a strike-slip transfer zone (Figure 1.2). Each terrane displays different characteristics of extension. Dokka (1989ab) showed that this regional extension was active dominantly from 22-20 Ma and that the direction of extension is NE-SW. As extension progressed, upper plate rocks were progressively dissected by faults causing these crustal blocks to tilt uniformly, akin to a stack of books or dominoes falling over. The strike of these rock units and the faults facilitating extension tend to be perpendicular to the direction of extension (see Wernicke, 1981; 1985). These terranes of the Mojave extensional belt all display evidence for the same direction of extension (NE-SW), although different amounts of extension.

### **Strike-Slip History**

Evidence for strike-slip faulting in the Mojave Desert has been recognized for decades. Dibblee (1961) observed that faults sub-parallel to the San Andreas fault display a similar sense of displacement, though lower magnitude, to the San Andreas fault. Geodetic strain studies (Sauber and others, 1986) showed that right-lateral motion is actively deforming much of the Mojave Desert. This strain was manifested in the 1992 Landers earthquake sequence which produced surface rupture with right-lateral

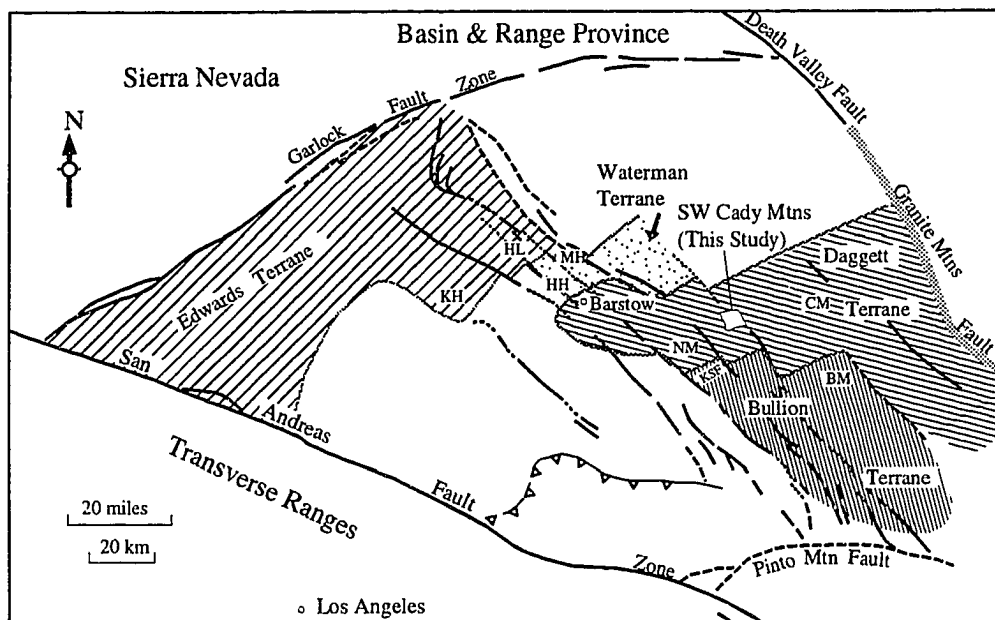


Figure 1.2 The Mojave Desert block. The Mojave Desert and immediate surroundings with boundaries of early Miocene extensional terranes from Dokka (1989). BM=Bullion Mountains, CM=Cady Mountains, HH=Hinkley Hills, HL=Harper Lake KH=Kramer Hills, KSF=Kane Springs Fault, MH=Mud Hills, NM=Newberry Mountains.

displacement on several faults in the southern and central Mojave Desert (see for instance Hauksson and others, 1992). The Landers earthquake sequence provides evidence for the connection of the San Andreas fault system as a system of faults through the Mojave Desert recently named the eastern Mojave shear zone (Dokka and Travis 1990a,b). The initiation of right-lateral movement on faults in the Mojave Desert is constrained to be later than ~ 13 Ma and possibly as young as ~ 5 Ma (Dokka and Travis 1990a,b). This young deformation has obscured older deformations and must be removed in order to evaluate these previous deformations.

Several models have been proposed for removing late Cenozoic strike-slip displacement in the Mojave Desert. Garfunkel (1974) proposed a geometric model to explain the pattern and sense of slip on northwest-striking faults. Because his model predicted that crustal panels defined by the northwest-striking faults should have rotated counter-clockwise through time, he suggested that his model could be tested using paleomagnetic methods. Luyendyk and others (1980) combined paleomagnetic data with the orientations of faults to propose a geometric model which satisfied implied vertical-axis rotations in southern California. Their model also predicted vertical axis rotation in the Mojave Desert (Luyendyk and others, 1980). Additional paleomagnetic data from southern California was used to refine the original model (Luyendyk and others, 1985; Carter and others, 1987). Most recently, Dokka and Travis (1990a) separated the region into structural domains and utilized fault-slip constraints, rotational information, geologic relationships, and iterative modeling to produce a reconstruction of the Mojave Desert block for middle Miocene time.

### **Vertical-Axis Rotations**

Paleomagnetic data from the southern Sierra Nevada was the first to provide evidence for tectonic rotation around the Mojave Desert (Kanter and McWilliams, 1982;

McWilliams and Li, 1985). Quickly more studies followed suggesting that tectonic rotation had occurred in the Mojave Desert. Ross (1988) and Ross and others (1989) suggested that clockwise tectonic rotation inferred from deflected paleomagnetic directions held by early Miocene volcanic rocks in the central Mojave Desert had been facilitated by early Miocene extension. Dokka (1989a) suggested that clockwise rotation in the Mojave Desert occurred after the main phase of regional extension and that the original direction of early Miocene extension was oriented N-S instead of NE-SW. Subsequently, other investigators related the increasing body of discordant paleomagnetic data in some way to activity synchronous with early Miocene regional extension (Bartley and Glazner, 1991; Valentine and others, 1993).

## **THIS STUDY**

The purpose of this study is to establish the relative timing between early Miocene regional extension and regional rotation. Prior to this study, paleomagnetic data from most lower Miocene strata of the Daggett terrane (Figure 1.2), suggest clockwise rotation (Ross, 1988; Ross and others, 1989), whereas data from post-extensional units (Peach Springs tuff; Wells and Hillhouse, 1989) indicate no rotation. The southwest portion of the Cady Mountains was chosen for this study because it was previously shown to have been affected by significant rotation (Ross, 1988; Ross and others, 1989) and appeared to contain stratigraphic and structural relationships which could be used to constrain the ages of extension and rotation. Careful geologic mapping and stratigraphic work, coupled with detailed paleomagnetic sampling were used to establish the tectonic history of the southwest Cady Mountains. This history was then applied to the problems of timing between the regional extension and rotation events. A model explaining regional early Miocene tectonic rotation has been produced and a



reconstruction of the Mojave Desert and immediately surrounding areas was constructed to form a base for the interpretation of older geologic events in this region.

## **ORGANIZATION OF THIS DISSERTATION**

This study is an integrated investigation into the Neogene tectonic history of the southwest Cady Mountains, and the significance of this information concerning the tectonic evolution of the Mojave Desert block. As such, each chapter represents an independent, yet integrated study which is presented in a journal paper format. Chapter 2 investigates the geology of the study area. Chapter 3 develops the paleomagnetic characteristics of the geologic units and integrates those data with the geology to formulate a tectonic history for the southwest Cady Mountains. Chapter 4 reviews paleomagnetic data on a regional scale, develops a tectonic model to explain these data, and presents a possible reconstruction of the Mojave Desert prior to regional rotation. Chapter 5 then summarizes these individual studies and presents an integration of this dissertation's results. Because each chapter is written such that it is a separate journal article, it will contain some overlap with other chapters. To date, Chapter 3 is in review for publication in the Geological Society of America *Bulletin*.

## **CHAPTER 2 - GEOLOGY OF THE SOUTHWEST CADY MOUNTAINS**

### **INTRODUCTION**

Tectonic events in the Mojave Desert block of southern California have received much study over the past years. The Neogene tectonic history of this area is quite varied and is slowly becoming understood. Two early Miocene tectonic events have been suggested by separate studies using different geological and geophysical techniques. These two regional events are 1) detachment-style extension (Dokka, 1980, 1986, 1989; Glazner, 1981, 1988; Glazner and others, 1989) and 2) clockwise vertical-axis rotation (Ross, 1988; Ross and others, 1989; Wells and Hillhouse, 1989; Bartley and Glazner, 1991; Valentine and others, 1993). Until recently, most investigators considered these two events to have been synchronous and genetically related. A recent study has demonstrated, however, that these are temporally distinct events (Chapter 3; Ross, in review, *Geological Society of America Bulletin*). The purpose of this paper is to describe relationships that establish the age and sequence of geologic events in the southwest Cady Mountains and then to relate these relationships to the evolution of the central Mojave Desert block.

### **General Geology**

Cenozoic volcanic activity commenced in late Tertiary time in the Mojave Desert block of southern California (Armstrong and Higgins, 1973; Nason and others, 1979; Dokka, 1989). Though volcanic and volcanoclastic units dominate early Miocene stratigraphy, few volcanic centers have been located to account for this wide spread volcanism. Volcanic activity continued through middle Miocene time and can be shown to have occurred before, after and synchronous with early Miocene regional extension (Dokka, 1986, 1989). An episode of early Miocene regional clockwise vertical axis rotation is interpreted from paleomagnetic directions from these volcanic deposits

(Chapter 3; Bartley and Glazner, 1991; Ross and others, 1989; Ross, in review; Valentine and others, 1993). Structural and stratigraphic relationships exposed in the southwest Cady Mountains are important because they allow for discrimination of the timing of these late Tertiary regional tectonic events. Detailed geologic and paleomagnetic analysis of the southwest Cady Mountains indicate that regional rotation is separate chronologically from early Miocene regional extension.

The effects of early Miocene detachment style extension are recognized throughout much of the Mojave Desert Block (Bartley and others, 1990; Dokka, 1986, 1989; Glazner and others, 1989). Deformation was partitioned into four extensional terranes, each separated by strike-slip transfer faults (Dokka, 1989; Figure 2.1). The typical effects of this extension are tilted upper plate fault blocks and transfer zones that lie above a brittle-ductile detachment surface. The Daggett terrane is bounded by a northeast-striking transfer boundary and contains numerous fault blocks having strata which dip to the southwest and are cut by northwest striking normal faults. Grooves and striations on normal faults in the Daggett terrane indicate that the dip direction of early Miocene volcanic rocks is roughly collinear with the direction of extension (Dokka, 1986, 1989). The southwest Cady Mountains, however, contain *northeast-striking* normal faults and tilted lower Miocene strata which dip to the *northwest*, somewhat anomalous with respect to similar elements in the rest of the Daggett terrane.

Recent paleomagnetic studies in the Daggett terrane show that lower Miocene volcanic units have been rotated  $\sim 50^\circ$  clockwise with respect to the early Miocene reference direction (Ross and others, 1989). Other early Miocene strata throughout the Mojave Desert block also suggest that vertical-axis rotations have occurred (Golombeck and Brown, 1988; Valentine and others, 1993). The timing of rotation is typically poorly constrained and has generally been thought to have been coincident with and/or

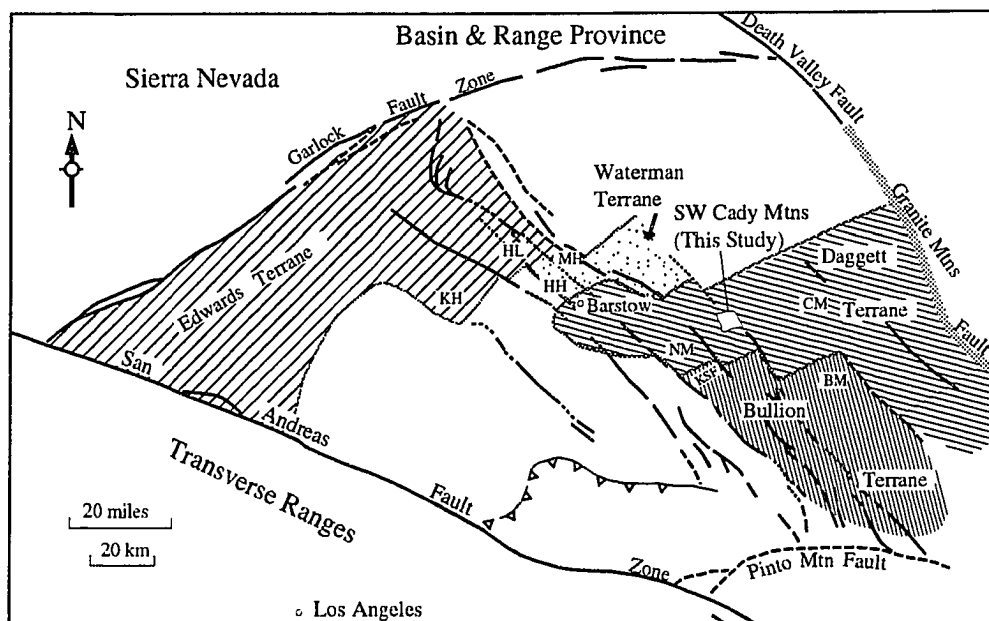


Figure 2.1 Early Miocene extensional terranes in the Mojave Desert. Depicts the Mojave Desert and immediate surroundings with boundaries of early Miocene extensional terranes from Dokka (1989). BM=Bullion Mountains, CM=Cady Mountains, HH=Hinkley Hills, HL=Harper Lake KH=Kramer Hills, KSF=Kane Springs Fault, MH=Mud Hills, NM=Newberry Mountains.

driven by early Miocene extension (Bartley and Glazner, 1991; Ross and others, 1989; Valentine and others, 1993). Dokka (1989), however, suggested that these tectonic events were not kinematically or temporally linked. The southwest Cady Mountains contain rocks of the appropriate age and structural position to test these hypotheses.

## **DESCRIPTIVE GEOLOGY OF THE SOUTHWEST CADY MOUNTAINS**

Bedrock units of the southwest Cady Mountains can be divided into pre-Tertiary crystalline basement and three mid to late Tertiary volcanic and volcanoclastic units. These units will be described in ascending stratal position.

### **Basement**

Basement rock consists dominantly of medium to coarse grained equigranular granite which displays hypidiomorphic granular and Rapakivi textures (salmon colored orthoclase is rimmed by white albite). No lower contact is exposed nor is an intrusive boundary with any country rock exposed. Small, fine-grained dioritic and aplitic dikes cut the pluton. These dioritic dikes have undulatory to inter-fingering boundaries with the pluton and macroscopic Rapakivi texture is often found near these dikes. Movement of the pluton appears to have deformed the diorite dikes, suggesting that the dikes were emplaced as a late phase while the pluton was still somewhat viscous. The aplite dikes typically have sharp, planar contacts and cut the diorite dikes.

Where younger volcanic and volcanoclastic rocks overlie the granite, the contact is often undulatory and weathered. The outcrop of granite steps down to the northeast with volcanic units lapping onto the granite and forming a local buttress unconformity. A partial weathering layer is found in some outcrops where the granite grades from relatively fresh outcrop to a red, weathered gneiss at the contact, with small amounts of weathered granite incorporated into the base of the immediately overlying strata.

This granite has been considered Mesozoic in age by previous mappers and was considered to be the same unit which is found in the central and northern Cady

Mountains (Dibblee and Bassett, 1966ab). Granites and quartz monzonites in the central Cady Mountains also display Rapakivi texture and yield dates of  $115 \pm 10$  Ma ("Lead alpha method" on zircon, reported in Dibblee and Bassett, 1966a) and  $139.6 \pm 2$  Ma (K/Ar method on biotite; Armstrong and Suppe, 1973; recalculated according to Dalrymple (1979) by Bortugno and Spittler, 1986). These dates suggest at least a Mesozoic age, but it is possible that these rocks are older and belong to a suite of Proterozoic ( $\sim 1.4$  Ga) anorogenic rocks which exist to the east of the study area (Anderson, 1989; Anderson and Bender, 1989).

### **Formation of Poe**

The formation of Poe (informal name) comprises volcanic and volcanoclastic strata which overlie the granitic basement along a distinctly non-planar nonconformity. This nonconformity steps down to the east ( $>100$ m relief) with the formation of Poe lapping onto this erosional surface forming local buttress unconformities on the sides of the downward steps. A measured section (Figure 2.2) is instrumental in describing the variability of this unit.

**Stratigraphic description.** The formation of Poe is best exposed in the core of a breached anticline found in the central portion of the study area. The basal deposit is typically a tuff which lies directly upon eroded and/or weathered granitic basement. This tuff is 2-4 m thick and exhibits minor fluvial reworking in some areas. This tuff is overlain by thickly bedded (4-50 m) lapilli to blocky tuff breccias which differ in clast size, type, and amount. These units can either be very local ( $\sim 50$  m) or crop out over a relatively large lateral extent ( $>1$ km). Clasts vary from pebble to boulder ( $>1$  m) in size, and may be rounded (tuff clasts) to angular (basalt and andesite clasts). Contacts between individual tuff breccias are often sharp, marked by an abrupt fining at the top or

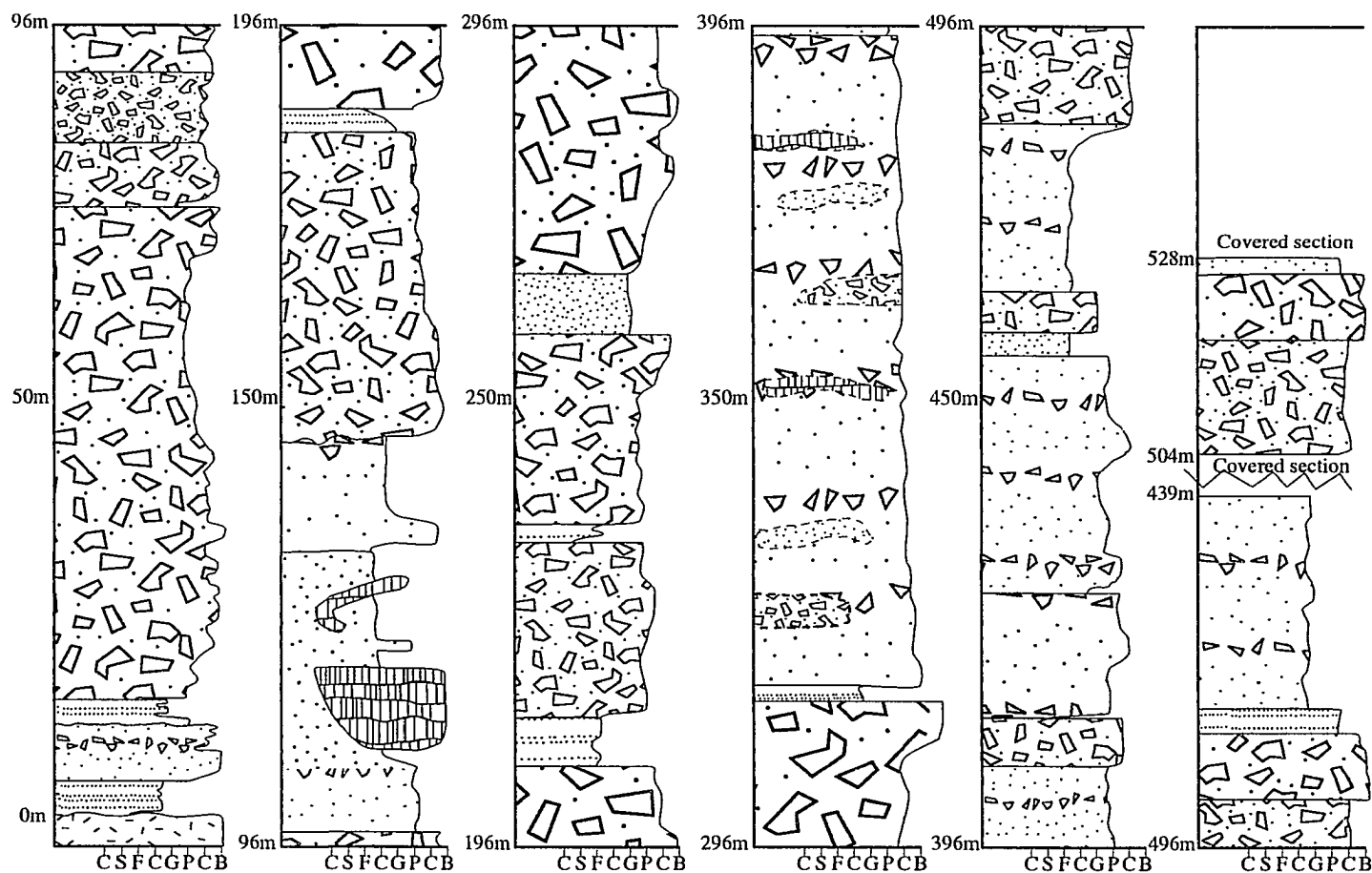


Figure 2.2 Measured section of the formation of Poe. All units above 0 m are volcanic or volcanoclastic tuff (massive and bedded), breccia and tuff breccia. Relative size of clasts in patterns is roughly proportional to the size of clasts in each unit. A scale of maximum clast size is shown (C, S, F, C, G, P, C and B designating clay, silt, fine and coarse sand, granule, pebble, cobble and boulder grain sizes.)

base of a unit. Both fining upward and coarsening upward patterns are observed in this section. Local finely laminated beds are occasionally found at the base of these tuff breccias. These beds show very fine wavy cross-laminations and may be volcanic surge deposits. Interspersed in these tuff breccias are massive ash deposits and local andesitic lava flows.

An apparently dismembered or transported package of very local units is found near the base of the measured section. This unit consists of a fine grained, massive green tuff with disjointed pods of andesite flow and breccia. These pods vary from 3-5 m thick by 10 m long to 10 m thick and 30 m long and are folded near their terminations. This unit and the pods it contains strike into an outcrop of granite basement, but overlying beds of tuff breccia continue across this area unbroken, suggesting a depositional abutment. This is interpreted to represent a landslide deposit which transported parts of previously formed beds and deposited them in a local valley.

Beds of monolithologic breccia are also present in the formation of Poe. These breccias are typically massive and consist of angular lapilli-size clasts of grey andesite in a matrix of fine andesite grains. The beds are clast rich, but matrix supported and the matrix is often weathered a salmon color. Paleomagnetic study of these units suggests that they hold primary magnetic directions and experienced a hot emplacement (Chapter 3; Ross, in review). These beds are some of the more laterally continuous units in the study area.

**Interpretation of depositional environment.** The massive thick bedded characteristics of many of these deposits, along with abundant large boulders and clasts that display random thermoremanent directions, suggest a debris flow (lahar) transport and depositional mechanism (Fisher and Schminke, 1984, p. 309). It is difficult to ascertain by outcrop characteristics whether these rocks were transported by primary volcanic or epiclastic processes. Only a few partially flattened pumice clasts, one clast



with radial cooling joints and no degassing pipes have been observed in >1km of section in the southwest Cady Mountains. Paleomagnetic studies, however do provide evidence which can be used to distinguish between volcanic or epiclastic deposits.

Paleomagnetic studies in the southwest Cady Mountains have been carried out by Ross (in review; Chapter 3). Thirty sites in various lithologies in the formation of Poe reveal varied paleomagnetic characteristics. Samples from ten sites display well-defined random within-site paleomagnetic directions. These results suggest that the bed sampled at each site was not deposited at elevated temperatures, but was most likely deposited cold due to an epiclastic process (ie: slump or debris flow). Seven of these paleomagnetic sites show non-random directions which move toward the reference inclination and are probably primary in origin. These seven sites are interpreted to have been cooled in place capturing thermoremanent magnetizations, most likely transported and deposited hot by primary volcanic processes (ie: eruptive blast or ash flow). Thus, the paleomagnetic is evidence consistent with both epiclastic and primary volcanic deposition in the formation of Poe.

The existence of ignimbrites, air fall tuff, tuff breccia and lava flows, interbedded with cold lahars suggests a depositional environment on the flank or near the base of a volcanic center (Cas and Wright, 1988, pp. 392 and 429). The mean paleomagnetic direction for sites showing primary magnetic directions has an inclination value very close to the inclination of the Miocene reference direction after correction for deformation. This agreement in inclination implies that the basic assumption of horizontal deposition used for the tectonic correction of the paleomagnetic sites is valid and that these rocks were deposited on slope of  $< \sim 5^\circ$ . However, the 95% confidence for this mean direction is large and could support  $15^\circ$ -  $20^\circ$  of initial dip on these beds. From the above characteristics of the formation of Poe, the most likely depositional environment is interpreted to be at or near the base of an active volcanic center.

**Age and correlation.** Geochronology from biotite separated from a tuff at the base of the formation of Poe provides a boundary for initiation for deposition. This stepwise  $^{40}\text{Ar}/^{39}\text{Ar}$  determination yields a disturbed release spectra with no plateau, and a  $^{40}\text{Ar}/^{36}\text{Ar}$  isochron intercept ( $264.4 \pm 9.7$ ) significantly removed from the atmospheric value of 295.5 ( Sample 910075, Appendix A). This biotite is interpreted to have been affected by some alteration to chlorite causing the disturbed release pattern. The best estimate of an age for this rock may be the total gas determination of  $28.1 \text{ Ma} \pm 1.0$ . This determination is poorly constrained and carries a low confidence for its accuracy due to the obvious violation of the closed system assumption for isotopic dating, but the total gas age is older than the base of the overlying formation of Troy Peak, consistent with the stratigraphy. The isochron intercept date is much older than the total gas age, suggesting that the total gas determination is a minimum age for this rock. Thus, deposition of the formation of Poe is poorly constrained to have initiated at  $\sim 28 \text{ Ma}$  or older. The age for the top of the formation of Poe is constrained by the  $\sim 26.6 \text{ Ma}$  age of the base of the overlying formation of Troy Peak discussed below. These dates suggest that the formation of Poe was deposited between  $\sim 28$  and  $\sim 26.5 \text{ Ma}$ , which is significantly older than previous workers have suggested for deposition of volcanic strata in the central Mojave Desert (ie:  $\sim 23\text{-}24 \text{ Ma}$ ; Armstrong and Higgins, 1973; Dokka, 1986, 1989; Glazner, 1980, 1988; Nason and others, 1979).

Correlation of these rocks to strata from surrounding areas is inexact and speculative and based on lithology, style of deposition and structural relationships. Rocks fitting the characteristics of andesitic to dacitic volcanic and volcanoclastic deposits which were affected by early Miocene extension can be found in the southern Cady (Dibblee and Bassett, 1966a; Glazner, 1988), eastern Cady (Mosely and others, 1982), Newberry (Dibblee and Bassett, 1966b; Dokka, 1986, 1989; ) and Rodman Mountains (Dibblee, 1964; field reconnaissance by the author).

## **Formation of Troy Peak**

The formation of Troy Peak (informal name) consists of a basal volcanic tuff breccia overlain by reworked tuff and basalt flows. The lower contact is an unconformity with a variable amount of angularity between the tuff breccia of the formation of Troy Peak and the formation of Poe (see Plates 1, 2). Plate 1 shows similar attitudes for the formations of Poe and Troy Peak in the central portion of the study area. However, this contact cuts down through the Poe section to the east and displays topography on its surface. The formation of Troy Peak is widely exposed in the southwest Cady Mountains and rims the core of a breached antiform in the center of the field area.

**Stratigraphic description.** In the central and southern portions of the field area the formation of Troy Peak comprises a distinctive monolithologic tuff breccia overlain by layered basalt flows. This tuff breccia is typically massive with cobble to boulder clasts of variably pumiceous andesite(?). Petrographic analysis of this rock shows plagioclase (sometimes large zoned phenocrysts with resorbed and embayed edges), hornblende and pyroxene phenocrysts in a glassy to pumiceous groundmass. Clasts from this tuff breccia carry random paleomagnetic directions above 450° C and non-random paleomagnetic directions below ~450° C, indicating that this is a primary volcanic deposit emplaced at ~450° C. Occasionally bedding is found in this ~150 m thick tuff breccia. Reworking of this unit produced long wavelength cross-stratification which is found locally beneath the overlying basalts.

A series of basalt flows up to ~100 m thick was deposited over variable topography on top of the tuff breccia. The contact is undulatory and shows local baking of the tuff. Petrographic analysis shows a glomerophytic texture of plagioclase and olivine phenocrysts (sometimes altered to iddingsite) in a very fine groundmass of

opaques, plagioclase and olivine. These basalts typically exhibit unidirectional magnetic behavior with well defined non-random site directions.

In the southern portion of the study area, the basalts are directly overlain by "Barstow Formation" sediments. The northern portion of the study area is comprised of a homoclinal stack of basalt and andesite flows interbedded with volcanic breccia. Faulting may duplicate part of this section, but this is hard to determine due to the local lateral extent of the deposits and discontinuous outcrop. The northern section contains an outcrop of sanidine-rich welded tuff which is ~18.6 Ma (see below). This tuff is macroscopically similar to an outcrop correlated by Glazner and others (1986) as the Peach Springs Tuff (~18.5 Ma; Neilson and others, 1990) in the southern Cady Mountains located about 20 km to the southeast. A sanidine-rich tuff located in the northern Cady Mountains (~17.9 Ma; Miller, 1980) is also essentially identical in hand sample to the welded tuff found in the southwest Cady Mountains.

**Interpretation of depositional environment.** The basal tuff breccia of the formation of Troy Peak was deposited on a tilted, eroded volcanoclastic section. Paleomagnetic studies suggest that this monolithologic breccia was deposited at greater than 450° C, indicating a hot, primary volcanic depositional process, such as an ash-flow. Basalt flows covered the study area and filled local topography on the tuff breccia. No flow direction has been determined for these basalts, but possible eruptive centers exist to the northeast of the study in the northern Cady Mountains. In the northern part of this study area, volcanic flows and breccias accumulated. These characteristics suggest a depositional environment close to an active volcanic center, yet far enough away for mostly large debris flows and extensive lava flows to reach.

**Age and correlation.** Hornblende separated from the monolithologic tuff breccia at the base of the formation of Troy Peak yields a fusion date of  $26.6 \pm 1.7$  Ma using  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology (Sample 910080, Appendix A). This is not the best of

determinations, because data concerning the thermal stability of this sample was lost due to the direct fusion of the sample. Unfortunately, the small sample size made a stepwise determination impractical with the equipment used. Samples of biotite (Sample 910078) and sanidine (Sample 910079) were separated from the welded tuff found in the northern portion of the study area. These samples give identical total gas ages (18.6 Ma), overlapping plateau ages ( $19.0 \pm 0.6$  Ma and  $18.7 \pm 0.3$  Ma), and very close isochron ages ( $19.1 \pm 0.3$  Ma and  $18.6 \pm 0.2$  Ma) using stepwise  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology on biotite and sanidine, respectively (see Appendix A). These age determinations suggest that the formation of Troy Peak was deposited from about 26.6 Ma through at least 18.6 Ma.

Though the central Mojave Desert is full of Tertiary volcanic deposits, the monolithologic breccia is a distinctive unit which underlies major basalt flows. This package is unique and has been found in two other places (to date) outside of the southwestern Cady Mountains. One of these areas lies ~10 km to the east of this study area immediately beneath the type Hector Formation of Woodburne and others (1974). The Hector formation consists of volcanic tuffs and volcanoclastic sedimentary units which overlie basalt flows and a monolithologic tuff breccia (Woodburne and others, 1974) which appears identical to the lower Troy Peak breccia in the southwest Cady Mountains (reconnaissance by author). A K-Ar determination from a tuff in the Hector Formation has yielded a 21.6 Ma age (Woodburne and others, 1974). This would place the age of the basalts and the underlying tuff breccia at older than 21.6 Ma, compatible with the ~26.6 Ma  $^{40}\text{Ar}/^{39}\text{Ar}$  determination for the tuff breccia in this study. Glazner (1988) describes the "formation of Argos Siding" of the Sleeping Beauty area of the Cady Mountains as comprising basalt to andesite flows, tuffs and clastic sedimentary deposits. The formation of Troy Peak may be similar to this unit, though this possible correlation has not been tested by field or petrologic analysis.

Another area in which this distinctive tuff breccia and overlying basalts crop out is in the Azucar Mine area of the Newberry Mountains, ~40 km west of the southwest Cady Mountains. The occurrence of this distinctive tuff breccia was first observed in this area by C. J. Travis, who showed the author the locality. If the correlation of these deposits is correct, then they must have been reasonably close to one another at the time of deposition. In the Hector area, these beds are tilted and dip ~25° SW, and at the Azucar Mine area they dip ~35° W. The tilt of bedding may suggest that either extension continued or occurred later in these areas than in the southwest Cady Mountains, or that these areas have experienced post extensional tilting of bedding.

### **"Barstow Formation"**

The "Barstow Formation" crops out in the southeast corner of the study area, conformably overlying basalts of the formation of Troy Peak. Due to similarities in age, gross lithology and sedimentary style with the type Barstow Formation in the Mud Hills, this section is referred to as the "Barstow Formation". Quotation marks are used because there is no reason to suggest that the strata which crop out in the southwest Cady Mountains were ever connected to the type Barstow Formation to form one continuous depositional unit.

**Stratigraphic description.** In general, this unit fines upward and eastward. The base of this unit is marked by a green porous tuff which is deposited ~3 m above the top of the underlying Troy Peak basalt. The first 6 m are dominated by a conglomerate of volcanic clasts (red andesite, black basalt and green altered basalt) in a green tuffaceous matrix. Some clast poor beds are apparent and contain silicified reeds and bone fragments within them. Near the top of this level, fossil teeth of *Merychippus* cf. *M. carrizoensis* were collected (identified by M.O. Woodburne, written communication, 1990; University of California, Riverside locality RV-9001). Prominent chert beds are found in these first 6 m of section in which quartz has nearly

totally replaced the original strata (limey-siltstone). The sequence of strata becomes finer at this point, consisting of light brown to chocolate brown tuffaceous siltstone and greenish grey to brown coarse to fine sandstones. These deposits are mostly poorly indurated massive beds which are 1 to 50 cm thick. The sandstones and siltstones grade into a silicified tuffaceous pebble conglomerate near 25 m which in turn grades into a thick cobble to boulder conglomerate at ~28 m ( Figure 2.3).

The cobble to boulder conglomerate is composed of angular to subrounded clasts of red andesite, black vesicular basalt and green altered tuff in a grey tuffaceous, fine grained to silty matrix. This conglomerate is at least 55 m thick at the west side of this local basin and inter-fingers to the east with brown to greenish silty sandstones. The sandstones on the east side of the basin are 10 to 50 cm thick and are variably covered by colluvium up to a very fine-grained finely laminated green tuff (165 m). This tuff unit is deposited throughout this local basin and varies from <3m thick at the east end to >10 m at the west side. The green lacustrine tuff has been quarried for "talc" (Dibblee and Bassett, 1966) and is exposed sporadically in excavation pits making it a valuable marker unit. Above this marker tuff unit on the east, the strata are dominantly covered, whereas rocks crop out almost continuously to the west.

Continuing upward from 165 m, brown to green siltstones and sandstones dominate. Bedding is usually 4 to 10 cm thick with occasional 1 to 3 cm laminated to cross-laminated sandstones. This section also contains a high proportion of tuffaceous sediment and calcite cement is common. A white tuff ~30 cm thick appears at 200 m and contains minor biotite. Above this tuff, light brown siltstones and coarse sandstones crop out before disappearing under a thin alluvial cover. An inferred fault separates these outcrops from a series of low ridges to the south which contain a light brown silty sandstone and a thick white tuff which are folded into a syncline.

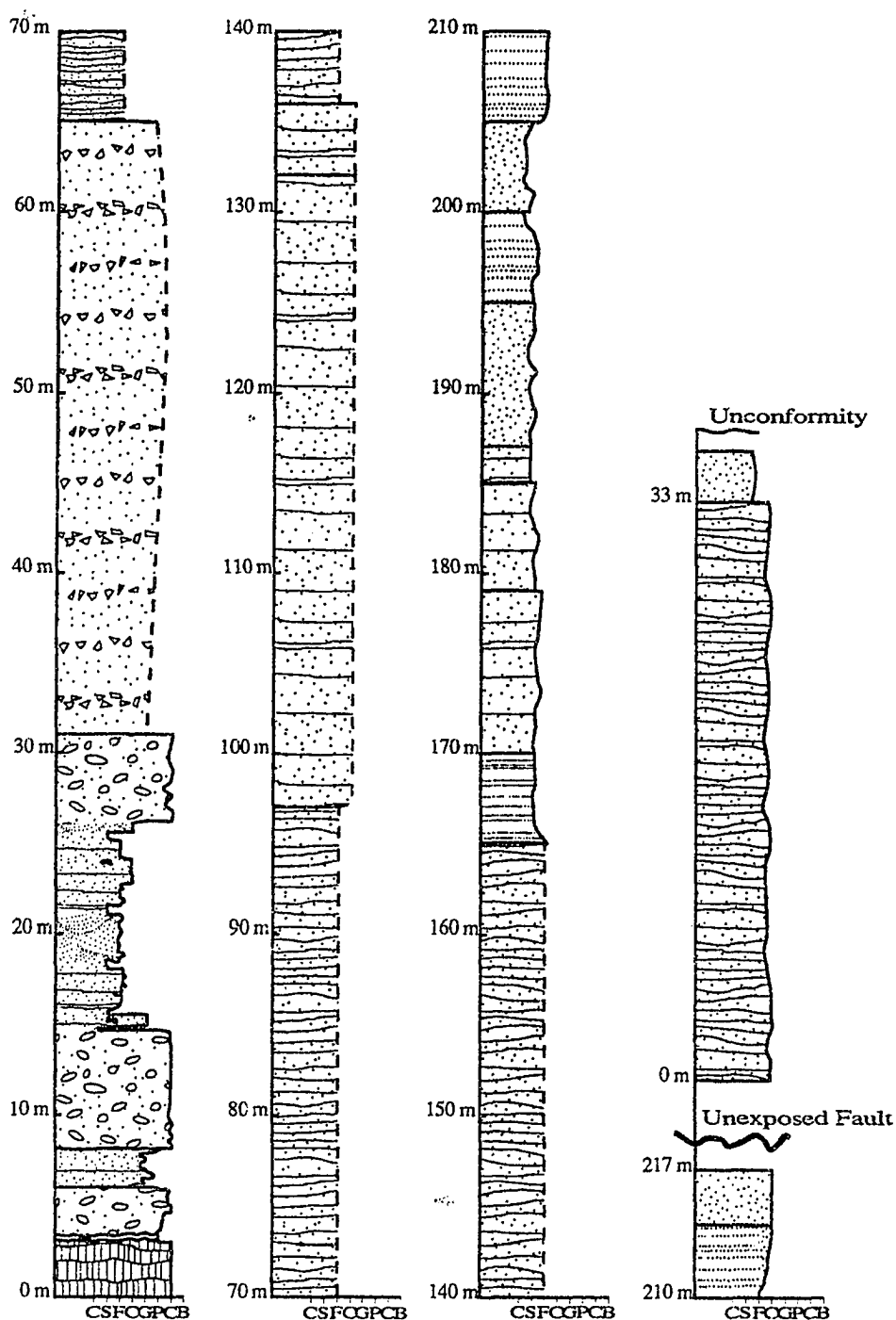


Figure 2.3 - Measured section of the "Barstow Formation". Lithologic units include basalt, siltstone and sandy siltstone, bedded, crossbedded and silty sandstone, conglomerate and tuff breccia. All units are volcanic or volcanoclastic. Dashed lines indicate areas which are mostly covered. C,S,F,C,G,P,C,B refer to the maximum grainsize in a unit.



**Interpretation of depositional environment.** The "Barstow Fm." is dominantly sandstone and siltstone which inter-fingers with coarser grained sediments to the west. These deposits are interpreted to be the products of a local fluvial to lacustrine depositional system. No diagnostic paleoflow indicators have been located to date, but the coarser sediments thin and fine eastward, suggesting a component of flow from the west (present coordinates). The western edge of the basin is characterized by the inter-fingering of the conglomeratic and fine-grained deposits, whereas the eastern edge of the basin does not appear to be exposed. These sediments are interpreted to have been deposited in a local basin by fluvial and lacustrine systems. The clasts are dominantly volcanic in origin and appear to have been derived from the underlying volcanic rocks. Fine grained tuffs do appear in this section, however, indicating active volcanism in the region during middle Miocene time.

**Age and correlation.** The age of the "Barstow Fm." can be constrained by a combination of vertebrate paleontology, magnetic stratigraphy and isotopic determinations. As mentioned above, remains of the diagnostic fossil horse *Merychippus cf. M. carrizoensis* occur near the base of these deposits, suggesting a late Hemingfordian to early Barstovian land mammal age (~16.5 - 15.5 Ma; M. O. Woodburne, written communication). Two isotopic dates have been determined on biotite separates from two tuffs in this section using the  $^{40}\text{Ar}/^{39}\text{Ar}$  method. One tuff (Samples 910077) gives a plateau age of  $14.0 \pm 0.3$  Ma and the other tuff (Samples 910076) provides a fusion date of  $17.6 \pm 0.2$  Ma (Appendix A). These paleontologic and isotopic ages provide control points to calibrate magnetostratigraphy for the "Barstow Fm." which suggest deposition as young as ~13.5 Ma. These combined methods indicate that the "Barstow Fm." was deposited between ~17.6 Ma and ~13.5 Ma, with the local base of deposition at ~ 16.5 Ma (the 17.6 Ma tuff is interpreted to have been faulted to the surface from a deeper portion of the basin).

The type Barstow Formation, which is found ~40 km NW of the study area, contains rocks of the same age (19.3 - 13.4 Ma) and a similar style of deposition to that of the southwest Cady Mountains (Woodburne and others, 1990; MacFadden and others, 1990). However, deposition in the southwest Cady Mountains was localized and probably never was physically connected to the Mud Hills depositional basin.

### **Quaternary Cover**

Quaternary to Recent strata cover Tertiary deposits in the southwest Cady Mountains. These deposits vary from uplifted older alluvial sandstones and conglomerates to active alluvial channels and aeolian sands. Because these deposits often comprise older volcanic clasts, they can be difficult to distinguish from Miocene volcanic breccia deposits. The dominant characteristic of the older alluvium is that it is discordant with respect to underlying bedding. These older alluvial deposits are well exposed along the southern flank of the study area (Figure 2.4; Plate 1) and dip to the southwest at ~11°. At the best exposure, the Quaternary(?) multi-lithologic conglomerate overlies a monolithologic tuff breccia of the formation of Troy Peak, but is also found overlying basalts of the formation of Troy Peak and sediments of the "Barstow Fm." The conglomerates are dominantly composed of sub-angular to rounded basalt and andesite clasts up to 1m in diameter, in a matrix of light brown tuffaceous sand and mud. Locally, pebbles and cobbles show imbrication indicating paleoflow in a south to southwesterly direction.

**Interpretation of depositional environment** The conglomeratic deposits are most likely relatively young alluvial fan deposits which have recently undergone uplift. Because these deposits dip to the southwest on the southwest limb of an anticline, their position may indicate very young folding of this study area. On the other hand, available information suggests that paleoflow was down the present dip. Because these are coarse grained deposits and may have been deposited with some initial

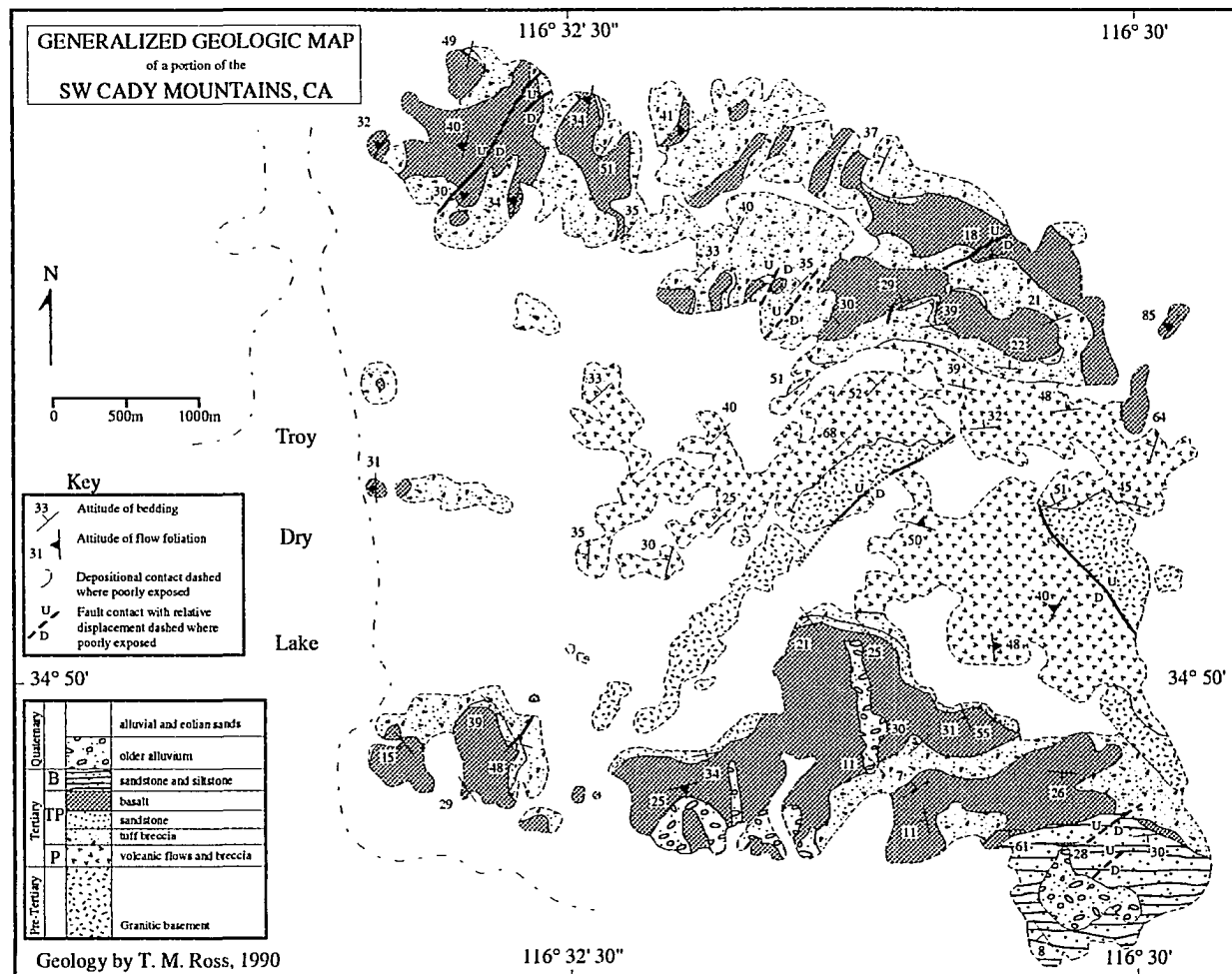


Figure 2.4 General geology of the southwest Cady Mountains. P, TP and B in legend designate the formation of Poe, formation of Troy Peak and the "Barstow Formation", respectively.

dip, their stranded nature may be simply due to vertical uplift and not to folding. The aeolian deposits are very young, for on a windy day in the study area, one can observe the active processes of transport and deposition of sand grains. Active alluvial deposits are confined to channels and fans.

## **STRUCTURAL RELATIONSHIPS**

### **Early Miocene Extension**

Regional early Miocene extension produced tilted upper plate fault blocks in the Daggett terrane which contains the southwestern Cady Mountains (Dokka, 1986, 1989). The dip direction of these upper plate fault blocks is consistently to the southwest with the exception of the southwest Cady Mountains, where analogous strata dip to the northwest.

**Structural position of Poe strata.** The strata of the formation of Poe dip steeply to the northwest and are unconformably overlain by the formation of Troy Peak. The angular unconformity of about  $15^{\circ}$  suggests that tilting of the formation of Poe occurred prior to deposition of the formation of Troy Peak. The basal portion of the formation of Poe is tilted more steeply than the upper portion, suggesting that deposition of the formation of Poe is at least partly syn-kinematic with the tilting event. Near the northeast end of the outcrop in the central portion of the mapping area, a north-plunging antiform is present in the formation of Poe strata. This fold is on strike with a strike-slip fault discussed below.

**Faults in the formation of Poe.** Two major faults cut the basement and the formation of Poe but don't cut the formation of Troy Peak. A northeast-striking fault, dipping steeply southeast, juxtaposes formation of Poe volcanic strata against granitic basement in the south-central portion of the study area. The offset is down to the southeast, suggesting normal motion, but no kinematic indicators have been observed to

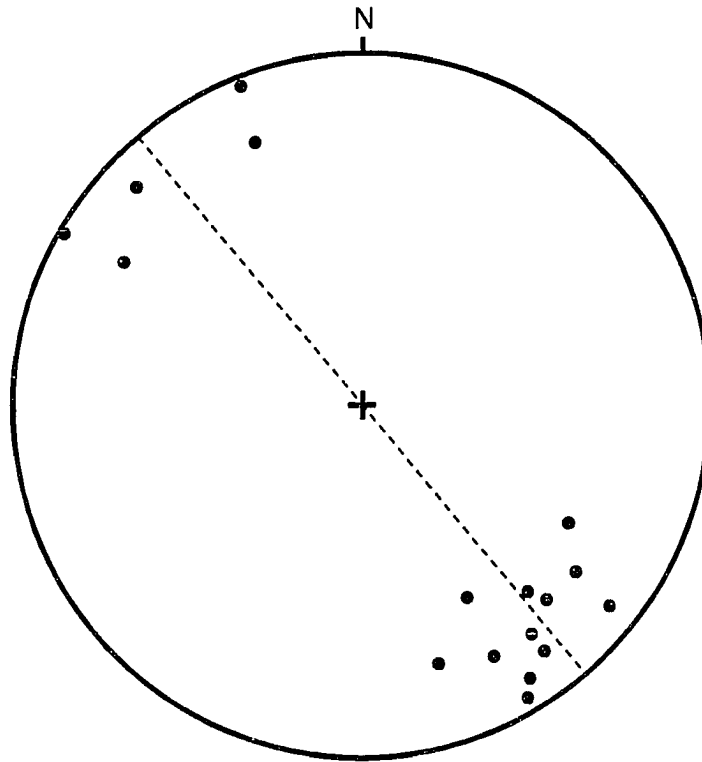


Figure 2.5 - Stereonet of slicken line data for NW-striking transfer fault. Lower hemisphere stereonet projection of plunge of grooves and striations with trends close to the regional strike of this fault.

corroborate with this interpretation. This fault is well exposed in only a few areas and disappears under alluvium to the southwest. This fault has a minimum throw of 360 m calculated near the middle of the fault.

A northwest-striking fault juxtaposes volcanic rocks against granitic basement in the central and southeastern portions of the study area. This fault dips moderately to steeply to the southwest and offsets the basal formation of Poe/basement contact  $\sim 0.7$  km in a right-lateral sense. Slicken stria are common in the 50 m wide fault zone, and are sub-horizontal when found on planes sub-parallel to the main fault (Figure 2.5). At its southern end, this fault disappears under alluvium, but the northern end projects into a fold which affects only formation of Poe strata. It is conceivable that the observed offset on the NW-striking fault could be due to down-to-the-east movement, i.e. strata dip to the NW and apparent offset is right-lateral. However, the juxtaposition of volcanic units (W) against granitic basement (E) on the southern portion of the fault suggests the opposite motion (down to-the-west). The sub-horizontal slicken-striations also support a lateral movement on this fault. For these reasons, this NW-striking fault is interpreted to be a dominantly right-lateral strike-slip transform fault that accommodated differences in style and amount of extension on the east and west.

The tilting of the formation of Poe is interpreted to have occurred during regional extension. The northeast-striking normal fault and the northwest-striking transform helped accommodate differences in upper plate extension. The present direction of tilting and orientation of these faults suggest that extension was directed NW-SE.

### **Post-Middle Miocene Structures**

A fold and a family of faults affect all units in the southwest Cady Mountains. Because these structures affect the "Barstow Formation", they are required to be younger than middle Miocene age. The antiform which dominates the central portion of the southwest Cady Mountains is best described by bedding in the formation of Troy

Peak (Figure 2.4, Plate 1). This fold may be classified as an upright, open, gently plunging anticline (*cf.* Fleuty 1964). A stereonet plot of poles to bedding in the formation of Troy Peak displays the isoclinal nature of the fold limbs and the gentle westward plunge of this fold (Figure 2.6). The "Barstow Fm." overlies the formation of Troy Peak with the same attitude and crops out on the south limb of the anticline, but not the north limb.

Minor northeast-striking faults cut all of the units exposed in the southwest Cady Mountains. These faults show variable offset amounts and directions. Figure 2.7 shows a stereonet plot of poles to fault planes and available kinematic data associated with these faults. These faults and this fold may be syn-kinematic or not, as the information for timing is poorly constrained for both events. The faults do not appear to have been affected by the folding, but the faults are typically of such small offset that it may be hard to tell which (if either) event came first. Stranded older alluvial fan deposits indicate that the southwest Cady Mountains either is being or has recently been uplifted. We cannot discern whether this uplift is associated with the folding and faulting.

There are two inferred faults in the study area (Plate 1), both of which are considered to be younger than middle Miocene age. A northeast-striking fault is inferred to cut rocks of the "Barstow Formation" near the southeastern tip of the study area. This fault is inferred due to the change in structural attitude of rocks of the "Barstow Formation" across an expanse of covering alluvium. The rocks to the north are gently dipping to the south, whereas the rocks to the south are dipping moderately to the south and are locally folded. The tuff from the "Barstow Formation" dated at  $14.0 \text{ Ma} \pm 0.3$  Ma was collected to the north and the tuff dated at  $17.6 \text{ Ma} \pm 0.2$  was collected to the south of this area. Because younger rocks are found to the north of older rocks (down

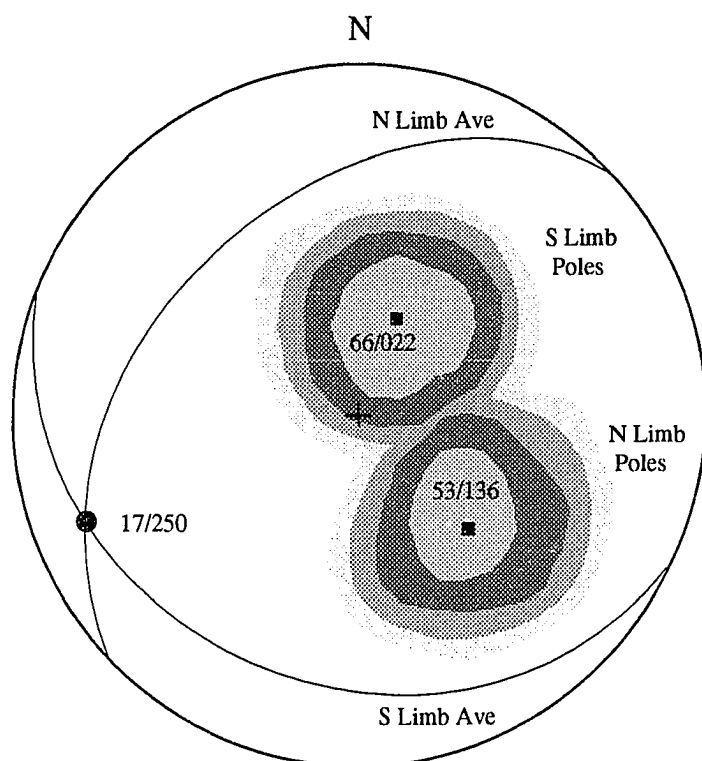


Figure 2.6 Stereonet of southwest Cady Mountains antiform data. Mean poles to limbs of anticline with a contour interval of 2 sigma. The intersection of the limbs indicates a gently plunging antiform at  $17^\circ$  toward  $250^\circ$ .  $N = 37$  for south limb and  $N = 40$  for the north limb. Lower hemisphere equal area plot.



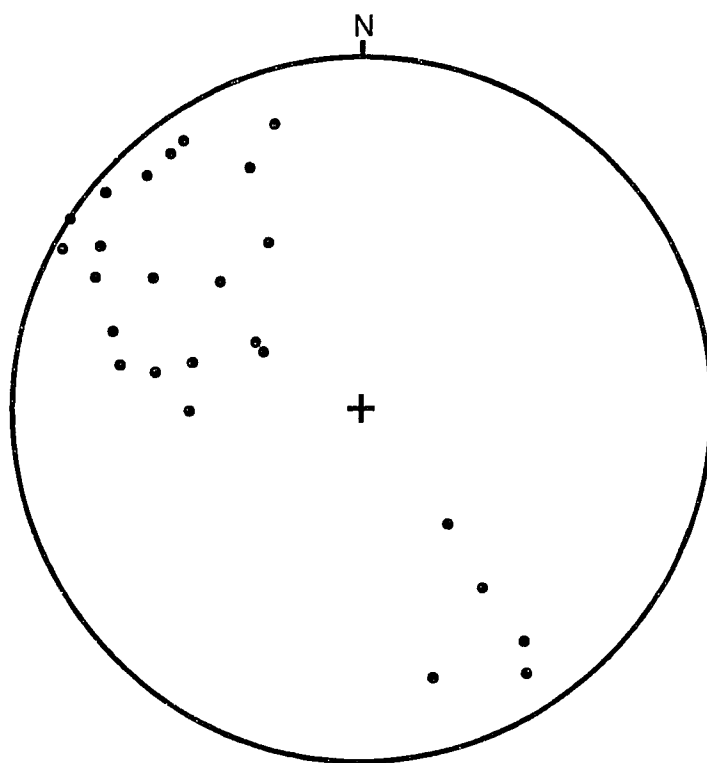


Figure 2.7. Stereonet of poles to NE-striking faults. Plotted on a lower hemisphere equal area stereonet.

section for southward dipping rocks) a structure of some kind must separate these areas. For this reason, a fault is inferred there of unknown displacement.

A southeast-striking fault is inferred in the northern portion of the study area (Plate 1) where rocks dip to the northwest. This fault separates rocks of the lower formation of Troy Peak from rocks from upper Troy Peak and is also interpreted to be concealed by alluvium. The rocks of the lower formation of Troy Peak give an age of  $26.6 \text{ Ma} \pm 1.7 \text{ Ma}$  and rocks in the upper portion of this formation yield an age of  $18.6 \text{ Ma} \pm 0.2 \text{ Ma}$ . The rocks which yield the younger age are found to the east of the rocks yielding the older age (apparently down section). A slight change occurs across a southeast-trending drainage, where contacts between rocks do not reappear as predicted. The only way to ameliorate this problem is to have a fault of unknown displacement separate these two areas.

Both of the above mentioned inferred faults display a heave that is up to the south. There is little evidence for the age of the northern fault except that it is younger than early Miocene (18.6 Ma), whereas the southern fault cuts rocks younger than 14.0 Ma. One possibility is that these faults have dominantly reverse displacement and may have been active in conjunction with the folding of the main portion of the study area. This hypothesis remains to be tested.

**Summary.** The upper Oligocene to lower Miocene formation of Poe was deposited upon a weathered granitic basement. These volcanic flows, tuffs and breccias were deposited near the flank of a volcanic center and were likely derived from that nearby source. Faulting and tilting of the formation of Poe occurred due to the effects of regional extension. The formation of Troy Peak was deposited after tilting of the formation of Poe and comprises a distinctive volcanic breccia and overlying basalt flows. The "Barstow Formation" was deposited conformably, yet with a distinct time gap, upon the formation of Troy Peak beginning in middle Miocene time. Sometime

after ~14 Ma, the southwest Cady Mountains was folded into an open antiform and cut by minor NE-striking faults. Since that time, the southwest Cady Mountains have been uplifted, stranding alluvial gravels and conglomerates on the southern side of the study area.

## **DISCUSSION**

### **Paleomagnetism**

Paleomagnetic studies in the central Mojave Desert block suggest an early Miocene regional vertical -axis rotation (Ross and others, 1989). This previous work suggested that the southwest Cady Mountains experienced ~124° of clockwise rotation since early Miocene time. Ross and others (1989) suggested that this ~124° of clockwise rotation was probably due to two separate rotations: one rotation coincident with early Miocene extension and a subsequent rotation due to interactions of active right-lateral faults through the Mojave Desert.

A more detailed study of the southwest Cady Mountains has produced mean paleomagnetic directions suggesting ~133° clockwise rotation for the formation of Poe, ~130° of clockwise rotation for the formation of Troy Peak, and ~67° of clockwise rotation for the "Barstow Formation" (Chapter 3; Ross, in review). The directions for the formations of Poe and Troy Peak are statistically identical, indicating that no relative rotation occurred between deposition of the formation of Poe and the formation of Troy Peak. Site directions from the "Barstow Formation" do not show any progressive decrease in rotation with age, indicating that the rotation which has affected them occurred after deposition of the youngest measured bed. This observation also indicates that the older clockwise rotation was complete prior to the deposition of the "Barstow Formation". These paleomagnetic data indicate two distinct clockwise rotations. The first rotation was ~63° clockwise and occurred after deposition of the formation of Troy Peak and prior to the deposition of the "Barstow Formation" (>~16 Ma), whereas the

second rotation was  $\sim 67^\circ$  clockwise and occurred entirely post-deposition of the "Barstow Formation" ( $< \sim 14$  Ma).

### **Tectonic History**

The structural, stratigraphic and paleomagnetic data submitted above can be combined to form a tectonic history for the southwest Cady Mountains. Widespread volcanism occurred over much of the central Mojave Desert during late Oligocene to early Miocene time. Volcanic centers were in or near the southwest Cady Mountains, producing the volcanic and volcanoclastic deposits of the formation of Poe. Faulting and tilting of this strata occurred due to regional extension without accompanying vertical - axis rotation. After local tilting had ceased, monolithologic tuff breccia and the basalt flows of the formation of Troy Peak were deposited. A gap in the rock record exists for the next few million years during which  $\sim 63^\circ$  of clockwise vertical -axis rotation took place. In the central portion of the range either no rocks were deposited, or these were subsequently removed prior to initiation of deposition of the "Barstow Formation"  $\sim 16.5$  Ma. Sometime after  $\sim 14$  Ma, the southwest Cady Mountains were folded into an antiform, cut by minor faults and experienced an additional  $\sim 67^\circ$  of clockwise rotation.

### **CONCLUSIONS**

Tertiary rocks of the southwest Cady Mountains are separated into three unconformity-bounded packages. Preliminary age control suggests that the formation of Poe was deposited at  $\sim 28$  Ma by volcanic and epiclastic processes from a nearby volcanic center. The formation of Poe experienced faulting and tilting of the strata due to extension prior to deposition of the base of the formation of Troy Peak at  $\sim 26.5$  Ma. Between  $\sim 26.5$  Ma and  $\sim 16$  Ma, a regional vertical axis rotation of  $\sim 50^\circ$  occurred. The "Barstow Formation" was deposited upon the formation of Troy Peak and subsequently experienced folding, faulting and clockwise vertical axis rotation.

The stratigraphy, geochronology, structures and cross cutting relationships observed in the southwest Cady Mountains constrain the ages of tectonic events in the central Mojave Desert block, as well as the southwest Cady Mountains. The age of extension in the study area may lie between the possible ~28 Ma age for lower formation of Poe strata and the ~26.5 Ma possible age for the base of the formation of Troy Peak. Regional early Miocene, clockwise vertical-axis rotation is constrained to have occurred after the ~26.5 Ma age of the lower formation of Troy Peak and prior to initiation of "Barstow Formation" deposition at ~16 Ma. The Peach Springs tuff result of Wells and Hillhouse (1989) in the Newberry Mountains suggests that the regional rotation was complete by ~18.5 Ma. The age for the youngest "Barstow Formation" tuff collected indicates that an additional ~67° of clockwise rotation occurred younger than 14.0 Ma.

These dates are apparently the oldest determinations for Tertiary volcanic rocks which have been acquired in the central Mojave Desert, pushing back the initiation of volcanism possibly to ~28 Ma. The conclusion that extension in the southwest Cady Mountains was complete by ~26.6 Ma is also different from other worker's interpretations for regional extension. More work is needed to establish better age control on these events, yet these preliminary conclusions are quite intriguing.

## **CHAPTER 3 - PALEOMAGNETIC STUDIES IN THE SOUTHWEST CADY MOUNTAINS**

### **INTRODUCTION**

Recent paleomagnetic data interpreted to indicate vertical axis tectonic rotation in the central Mojave Desert (Ross and others, 1989) have inspired several hypotheses to explain this phenomenon. Most hypotheses suggest a genetic link between well documented early Miocene regional extension and tectonic rotations suggested by paleomagnetic data (Ross and others, 1989; Bartley and Glazner, 1991; Valentine and others, 1993). In contrast, Dokka (1989) suggested that regional vertical-axis rotation occurred after major regional extension such that the two phenomena were not genetically linked. This paper reports a geologic observations and paleomagnetic data from the southwest Cady Mountains in the central Mojave Desert (Figure 3.1), an area where these competing hypotheses could be tested. This study bears on two major questions concerning the relationship between early Miocene extension and regional vertical axis rotation in the Mojave Desert block: (1) what is the temporal relationship between extension and rotation; and (2) what was the original direction of extension in the Mojave Desert region?

The Mojave Desert block is considered a tectonic province bounded by the San Andreas fault and the Garlock fault, extending eastward to the southward extension of the Death Valley fault zone, roughly equivalent to 116° west longitude (after Dokka, 1983; Figure 3.1). This nomenclature is adopted to distinguish this tectonic province from the geographic and biologic provinces known as the "Mojave Desert". A further convention is followed concerning the deformation of parts of the earth's crust. The rotation of a crustal block about a sub-horizontal axis is referred to as tilting, whereas

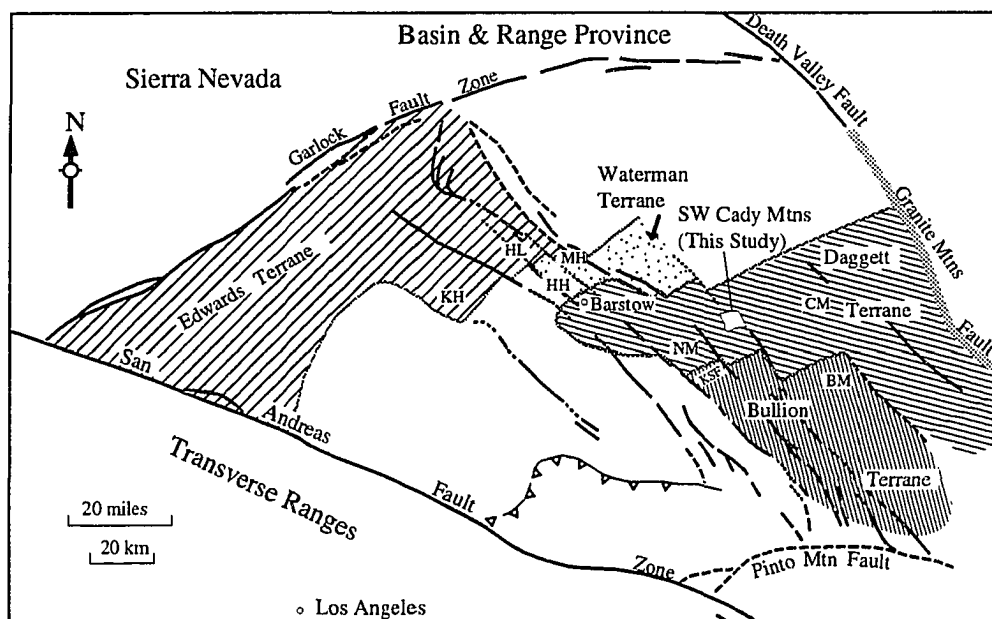


Figure 3.1 Boundaries of early Miocene extensional terranes of the Mojave Desert. The Mojave Desert and immediate surroundings with boundaries of extensional terranes from Dokka (1989). BM=Bullion Mountains, CM=Cady Mountains, HH=Hinkley Hills, HL=Harper Lake KH=Kramer Hills, KSF=Kane Springs Fault, MH=Mud Hills, NM=Newberry Mountains.

the rotation of a crustal block about a vertical axis is referred to as rotation. Reference to any rotation about an inclined axis will be explicitly noted.

### **Early Miocene Extension and Rotations**

Regional detachment-style extension affected the Mojave Desert block in early Miocene time, accommodating the tilting of upper-plate fault blocks and exhumation of mid-crustal metamorphic rocks (Dokka, 1986, 1989; Dokka and Woodburne, 1986; Glazner, 1988; Glazner and others, 1989; Bartley and others, 1990; Walker and others, 1990a; Henry and Dokka, 1992). Thermochronology of rocks affected by this extension indicate activity mainly between 22 and 20 Ma (Dokka, 1986, 1989; Dokka and others, 1991; Henry and Dokka, 1992). Dokka (1989), referred to this extensional system as the "Mojave extensional belt" and separated this system into four domains of extension (shown in figure 3.1) kinematically linked by strike-slip faults (transfer boundaries). In contrast, Bartley and others (1990) refer to the "central Mojave metamorphic core complex" which occupies a large portion of the Waterman terrane of Dokka (1986, 1989). The southwest Cady Mountains, the focus of this study, are located in the Daggett terrane of the Mojave extensional belt.

Paleomagnetic data from lower Miocene volcanic rocks in upper-plate fault blocks of the Daggett terrane were interpreted to indicate that these rocks experienced  $49^{\circ} \pm 20^{\circ}$  of clockwise rotation sometime after their deposition (Ross and others, 1989). These moderate to steeply tilted rocks, sampled over a 3200 km<sup>2</sup> area, were affected by regional scale early Miocene extension (Dokka, 1989; Ross and others, 1989). Data for the southwest Cady Mountains were interpreted to indicate  $124^{\circ} \pm 16^{\circ}$  of clockwise rotation (Ross, 1988; Ross and others, 1989). Paleomagnetic results from an outcrop correlated with the ~18.3 Ma Peach Springs Tuff (Wells and Hillhouse, 1989; Neilson, and others, 1990) provide a minimum age for this ~50° regional rotation. This welded



tuff outcrop is nearly flat-lying, unconformably overlies tilted lower Miocene volcanic rocks in the Newberry Mountains, and gives a paleomagnetic direction statistically indistinguishable from the Peach Springs Tuff on the Colorado Plateau (Wells and Hillhouse, 1989). Thus regional rotation took place after deposition of the lower Miocene volcanic rocks (~23-21 Ma; Dokka, 1986), but prior to about 18.3 Ma (Ross and others, 1989; Wells and Hillhouse, 1989; Neilson, and others, 1990).

### **Contrasting Hypotheses**

Ross and others (1989) reasoned that because the apparent age of the rotation (23-18 Ma) overlapped with the age of regional extension (22-20 Ma), these two tectonic events were most likely coincident in time and genetically related. Bartley and Glazner (1991) recognized an overlap in age and a coincidence in present extensional direction, and proposed that extension in the central Mojave Desert block was coeval and kinematically linked with extension in the Colorado River extensional corridor. Valentine and others (1993) also advocated that extension in the Mojave Desert block was originally oriented NE-SW, proposing that suspected rotations in the Mojave Desert block can be explained by interaction of crustal blocks with the lateral boundaries of extension. Dokka (1989) suggested that regional rotation occurred after major extension and interpreted paleomagnetic data to indicate that the original extension direction for the Mojave extensional belt was oriented ~N-S.

With the exception of Dokka (1989), existing hypotheses imply that early Miocene extension and vertical axis rotation in the Mojave extensional belt are genetically related and predict that the upper-plate fault blocks have rotated with respect to lower plate rocks. These hypotheses can be tested by careful evaluation of temporal relationships between extension and rotation in the Mojave Desert block, and by comparing the extension direction indicated by structures and kinematic features in upper and lower

plate rocks. The geology of the southwest Cady Mountains allows extended and post-extension strata in the Daggett terrane to be studied for quantitative analysis of rotation using paleomagnetic methods to satisfy the first part of the test, and recognized relationships of regional extension are interpreted to achieve the second portion of the test. This paper presents new evidence which indicates that early Miocene regional clockwise rotation in the central Mojave Desert followed significant extension, implying that the rotation must be removed to obtain the original extension direction and that the original early Miocene extension direction was ~N-S.

## **GEOLOGIC SETTING OF THE SOUTHWEST CADY MOUNTAINS**

### **General Relations**

The southwest Cady Mountains are located in the central Mojave Desert, about 30 km east of Barstow, California (Figures 3.1 and 3.2). The range is bounded by Troy dry lake on the west, the Cady fault on the north and alluvial cover to the east and south. Miocene volcanic and sedimentary rocks occur throughout the field area and can be separated into three packages bounded by unconformities. Informal names for these units used in this paper are, from oldest to youngest: the formation of Poe, the formation of Troy Peak and the "Barstow Formation".

The formation of Poe consists dominantly of volcanoclastic breccias with interbedded tuffs and basaltic to andesitic flows and is named for the abandoned town site of Poe on nearby US Route 66. These rocks were deposited on a weathered pre-Tertiary granitic basement which had local topographic relief of up to 100 m and dip up to 60° NW at the base of this unit and shallow up-section to about 35° (Figure 3.2). The formation of Troy Peak contains a distinctive monolithologic volcanic breccia and overlying basalt flows that crop out on Troy Peak, the highest point of the southwest

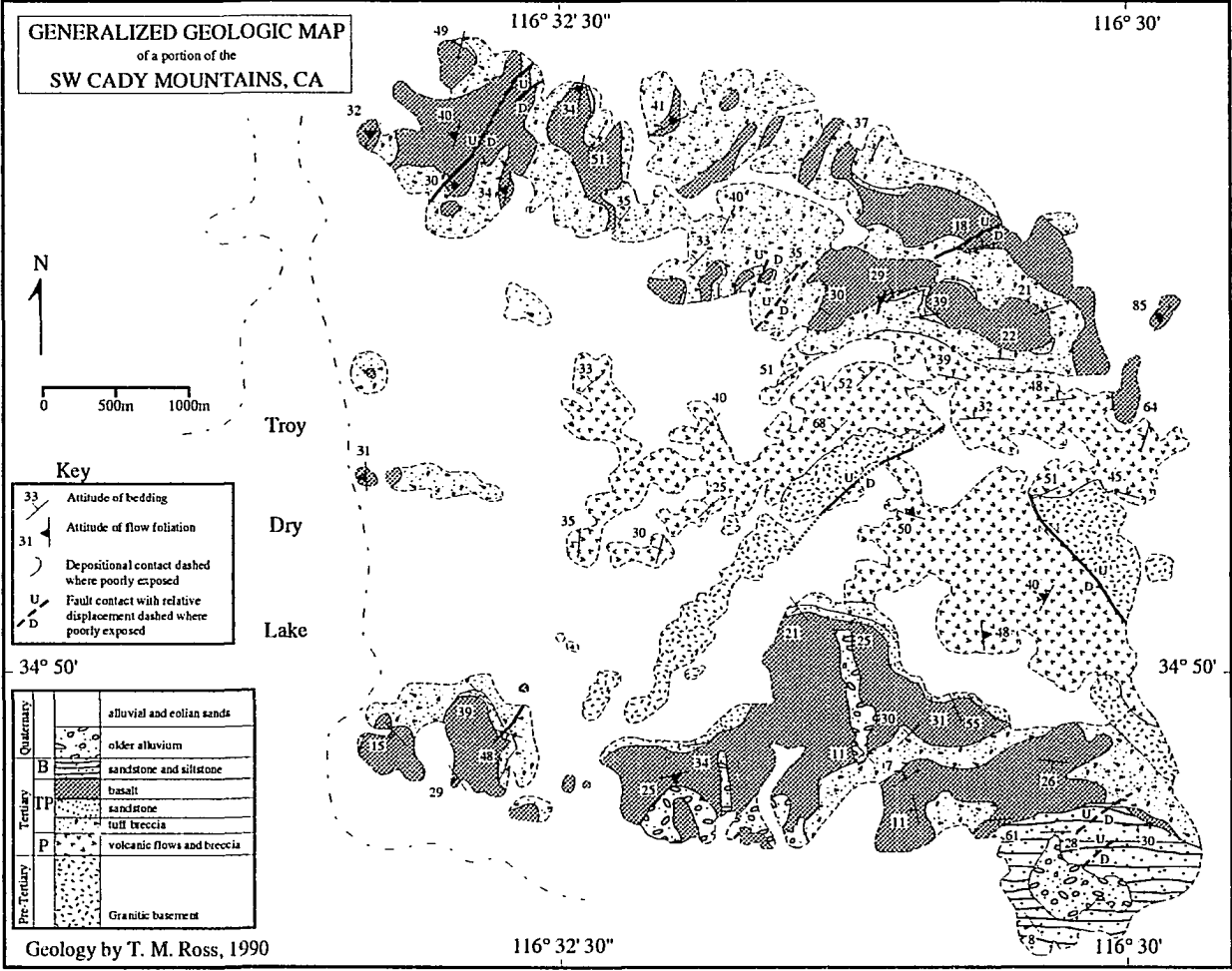


Figure 3.2 Geologic map of the southwest Cady Mountains. P, TP and B in legend designate the formation of Poe, formation of Troy Peak and the "Barstow Formation", respectively.

Cady Mountains. These rocks overlie the formation of Poe unconformably ( $\sim 15^\circ$  decrease in strike and  $\sim 10^\circ$  shallower dips) and has been folded into an upright, open, gently plunging anticline (*cf.* Fleuty, 1964).

The "Barstow Formation" is applied locally to this section due to the similarities in age, style of deposition, and lithology with the type Barstow Formation in the Mud Hills, but there is no reason to consider that these localized middle Miocene deposits were ever continuous (see Woodburne and others, 1991). These rocks overlie the formation of Troy Peak with no angular discordance, but a significant time gap is suggested by a correlation of the formation of Troy Peak with strata underlying the nearby type Hector Formation ( $>21.6$  Ma; Woodburne and others, 1974) and a late Hemmingfordian to early Barstovian mammal age ( $<\sim 16.5$  Ma) for the base of the "Barstow Formation." The "Barstow Formation" consists of basal conglomerate which grades into fluvial and lacustrine tuff, sandstone and siltstone deposits up section. A fossil quarry located near the base of this unit has produced remains of the Miocene horse *Merychippus cf. M. carrizoensis* (M. O. Woodburne - personal communication, 1990; Ross and others, 1991). The occurrence of these fossils suggests that the base of the "Barstow Formation" is younger than about 16.5 Ma. An  $^{40}\text{Ar}/^{39}\text{Ar}$  analysis of biotite separated from a tuff in this section gives a plateau age determination of  $14.0 \pm 0.3$  Ma (T. Ross unpublished data), suggesting a middle Miocene age consistent with the late Hemmingfordian to early Barstovian mammal age of the horse fossils.

### **Structural Relations**

The pre-Tertiary basement and overlying formation of Poe are cut by faults which do not cut younger rocks. One of these faults strikes NE and places volcanic and volcanoclastic rocks against granitic basement in a normal sense (Figure 3.2). Displacement on this fault dies quickly to the NE. A NW-striking fault zone in the

eastern portion of the southwest Cady Mountains also places volcanic rocks against granitic basement (Figure 3.2). This fault displaces the formation of Poe/basement contact ~0.7 km in a right-lateral sense and folds overlying beds of the formation of Poe. The NW-striking fault, therefore, is interpreted to be a strike-slip fault (local transfer zone), and the NE-striking fault is interpreted to be a normal fault, both of which facilitated early Miocene extension in the southwest Cady Mountains. The formation of Troy Peak is folded into a gently westward plunging anticline. There is no angular discordance between the formation of Troy Peak and the "Barstow Formation" (Figure 3.2). This observation is interpreted to indicate that the folding is younger than deposition of the "Barstow Formation." Minor northeast striking faults cut both the formation of Troy Peak and the "Barstow Formation", consistent with deformation younger than the age of the "Barstow Formation".

The field relationships presented above are interpreted to indicate the following tectonic history: (1) Regional extension occurred during or after deposition of the formation of Poe and tilting associated with extension had ceased in the southwest Cady Mountains prior to deposition of the formation of Troy Peak; (2) The formation of Troy Peak was deposited unconformably on these tilted rocks and was not deformed until after the "Barstow Formation" was deposited; and (3) Following deposition of the "Barstow Formation", rocks of the southwest Cady Mountains were folded into an open anticline and cut by minor faulting. Paleomagnetic data were obtained for these rocks to determine the timing and mechanisms of early Miocene extension and vertical axis rotation in the southwest Cady Mountains.

## PALEOMAGNETIC METHODS

### Analytic Methods

Paleomagnetic analysis was carried out on 434 samples from 65 sites in the southwest Cady Mountains. Oriented cores and hand samples (blocks) were gathered from volcanic flows, volcanoclastic breccia and lacustrine tuff and mudstone beds. The cores were collected *in situ* using a gasoline powered drill with a 2.5 cm diameter bit, then oriented using a magnetic compass and where possible, a sun compass. Hand samples were oriented using a magnetic compass in the field and reoriented and drilled in the laboratory producing 2.5 cm diameter cores. Each block is treated as one independent paleomagnetic sample. Local variations in the magnetic field were checked and outcrops with strong local magnetic variations were avoided. Orientation of samples by these techniques is estimated to be within  $\pm 2^\circ$  for cores and  $\pm 4^\circ$  for block samples.

The magnetic characteristics of rocks sampled were investigated using stepwise thermal and alternating field (AF) demagnetization techniques. All remanent magnetization measurements were obtained using a CTF three-axis superconducting cryogenic magnetometer at Louisiana State University. Thermal demagnetization utilized heating in a three-zone furnace powered by Lindberg components and protected from the earth's magnetic field by three cylindrical mu-metal shields. Samples were AF treated using a tuned solenoid driven by a Behlman AC power supply. Two samples were selected from most sites for the study of IRM acquisition in order to identify the dominant magnetic carrier for each site.

Pilot samples showed that stepwise thermal demagnetization was more effective than AF treatment in resolving characteristic magnetizations in most rocks. All samples were subjected to at least 15 thermal demagnetization steps and most were subjected to

more than 20 steps. Magnetization information was evaluated using stereonet plots and orthogonal demagnetization diagrams (Zijderveld, 1967), and directions of magnetization interpreted to be characteristic of the rocks studied were calculated using the principal component analysis method of Kirschvink (1980). Components are considered to be distinct if three or more consecutive points lie close to the same line (mean angular deviation typically  $< 10^\circ$ ). Site mean directions and their associated errors have been calculated using the methods of Fisher (1953).

Some sites exhibit magnetizations with overlapping unblocking temperature spectra, as indicated by curved trajectories on orthogonal demagnetization diagrams. Characteristic magnetizations were separated using the analysis of magnetization planes following Halls (1976); and Kirschvink (1980), and site mean directions and their associated errors were calculated by the method of Bailey and Halls (1984).

### **Application of Tectonic Corrections**

To assess vertical axis rotation of the tilted beds sampled in this study, the data for each site have been "corrected" by untilting the strata about an axis or sequence of axes to return bedding to the horizontal datum. The correction used is dictated by the observed structural geology and the present bedding orientation. Field relations indicate that tilting of formation of Poe strata was followed by deposition of the formation of Troy Peak and then the "Barstow Formation", and all three sequences were later folded. Removal of the effects of folding from the formations of Troy Peak and Poe is accomplished by first restoring the plunge of the anticline ( $17^\circ$ ,  $S70^\circ W$ ) to horizontal, then untilting the beds about the new strike axis to return them to horizontal (*cf.* MacDonald, 1980). This procedure returns a paleomagnetic direction to its original inclination, assuming the bedding was deposited horizontally, and its original declination if no vertical axis rotation has occurred. In this study, the plunge of the fold

is shallow ( $17^\circ$ ) and contributes only a small amount to the tectonic correction, thus an error in the determination of the plunge of this fold produces only a small error in the tectonically corrected declination. Returning the bedding of the formation of Poe to horizontal is more involved because those rocks were tilted prior to folding. First, the folding of the anticline was removed in a manner similar to both the formation of Troy Peak and the formation of Poe, using the mean orientation of the formation of Troy Peak bedding on the northern limb of the anticline. Then, the pre-folding tilt of bedding is removed by untilting about the new strike of the bedding, using the new dip amount to bring the bed to horizontal.

## **PALEOMAGNETISM**

The following discussion of paleomagnetic data is conducted out of stratigraphic order. In order to assess their tectonic significance and/or the age of acquisition of stable magnetism of the formation of Poe, data from these rocks are compared to the mean direction for the formation of Troy Peak. Data from the formation of Troy Peak will be discussed first, followed by the formation of Poe, and then the "Barstow Formation". When referring to the magnetic properties of samples and sites, the terms "well-grouped" (non-random within site characteristic directions) and "convergent" (displays trajectories which converge linearly to the origin of an orthogonal demagnetization diagram) will be used for brevity.

### **Formation of Troy Peak**

One hundred samples were collected from twelve sites in the formation of Troy Peak. Eight sites located in basalt flows in both the northern limb (6) and the southern limb (2) and one site in a tuff breccia on each fold limb gave interpretable information. Two additional sites in a tuff breccia on the south limb of the anticline show multi-



component, non-convergent demagnetization response, are not well-grouped, and are not used for tectonic analysis.

The eight sites in basalt flows all show similar magnetic behavior with a low unblocking temperature, low coercivity magnetization component which is typically aligned near the present earth's magnetic field direction. After removal of this component, most samples display well-defined, convergent characteristic magnetizations which are well-grouped (Figure 3.3A). IRM acquisition in these basalts is very rapid in inductions below 300 mT, followed by a slight gradual rise in IRM up to saturation by 700 - 800 mT (Figure 3.3C). This IRM behavior suggests a magnetic dominance by a low coercivity phase such as magnetite, but that a high coercivity phase is also present. Stepwise thermal demagnetization reveals unblocking temperatures typically below 600° C indicating that magnetite is the low coercivity phase and that possibly a relatively low-unblocking temperature hematite or maghemite may be the high coercivity phase (Figure 3.3A, C). The magnetization carried by hematite (or maghemite), is typically co-linear with that carried by magnetite. Site mean directions for the formation of Troy Peak basalts have been calculated excluding samples which are not convergent (2 samples total) or which display directions far from the site mean direction (6 samples total). All sites in the formation of Troy Peak give reversed polarity magnetizations suggesting that secular variation of the earth's magnetic field is probably not adequately averaged.

Six sites were established in a thick section of basalt flows on the north limb of the anticline. To evaluate the time span over which these flows were erupted, the mean direction for each site has been plotted on a stereonet with associated 95% confidence values ( $\alpha_{95}$ ; Figure 3.4A). If the  $\alpha_{95}$ s of two adjacent flows overlap, then these sites are averaged to form one cooling unit. Figure (3.4A) shows that adjacent sites 9033 and 9034 overlap, as do sites 9037 and 9038. The site means of the other two sites are significantly different from immediately adjacent sites. Sites 9033 and 9034 have been

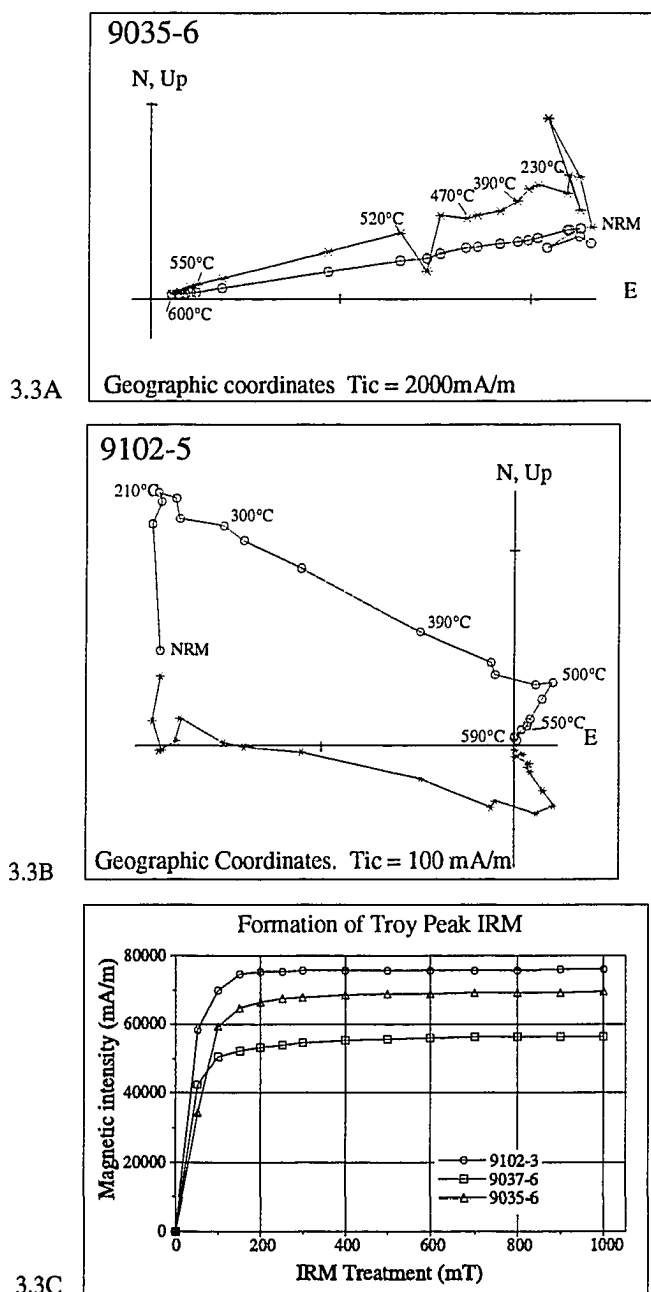


Figure 3.3 Paleomagnetic diagrams from the formation of Troy Peak. Circles lie in the vertical plane and stars in the horizontal plane. A) Paleomagnetic vector diagram from a basalt flow showing typical stable, convergent behavior under thermal demagnetization. B) Paleomagnetic vector diagram from a sample of monolithologic breccia showing three distinct magnetic directions under thermal demagnetization. The moderate temperature component is consistent throughout the site and is interpreted to be a TRM from cooling of this volcanic unit. C) IRM acquisition spectra of samples from two basalt flows (9035-6, 9037-6) and one monolithologic breccia unit (9102-3). All spectra show a dominance of a low coercivity component which is probably magnetite.

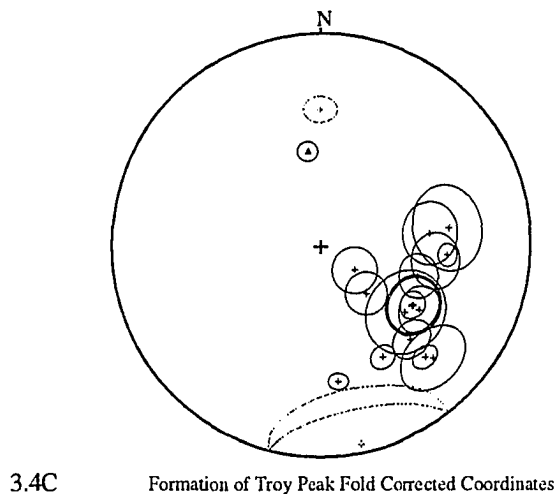
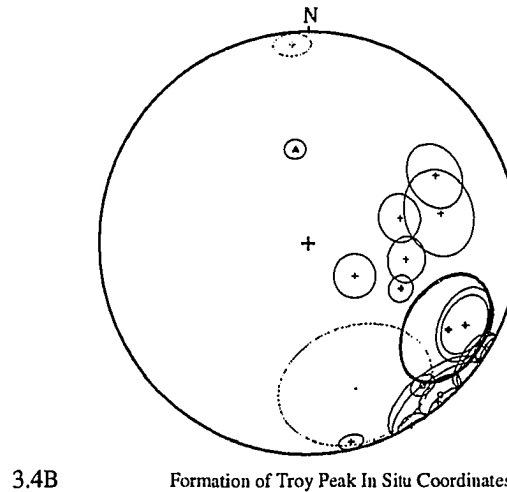
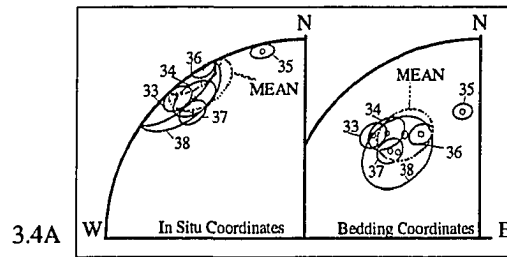


Figure 3.4 Paleomagnetic directions of the formation of Troy Peak. Equal area projection: + = lower hemisphere, o = upper hemisphere, solid triangle is Miocene normal polarity reference direction calculated from Deihl and others (1983). A) Mean directions for sites 9033-9038 (basalt flows, in stratigraphic order, base to top, respectively) and the overall mean direction for these sites with 95% confidence ellipses. This plot displays secular variation in a section of basalt flows on the north limb of the anticline. B) All in situ site determinations for the formation of Troy Peak (referred to normal polarity) and the in situ mean direction (heavy line). C) All site determinations for the formation of Troy Peak (referred to normal polarity) and the mean direction (heavy line) after application of tectonic correction.

averaged to form a cooling unit (9033/34) and sites 9037 and 9038 have been similarly averaged to form a cooling unit (9037/38). The clockwise path described by the mean directions is similar to secular variation behavior on the order of  $10^3$  yrs shown by archeomagnetic results (see, for example: McElhinney (1973, p.20) or Butler (1991, p.10-12)). The systematic variation in directions displayed by this small number of sites is interpreted to suggest that some secular variation has been averaged.

Four sites located in a tuff breccia that crops out throughout the field area gave variable results. Site 9101 shows random convergent directions and site 9104 shows multi-component, non-convergent behavior. These sites were not included in tectonic analysis. Sites 9102 and 9125, located on the south and north limb of the anticline, respectively, display three separate magnetization components during thermal demagnetization (Figure 3.3B). A present field overprint is removed by about  $180^\circ\text{C}$  revealing a consistent west-directed negative inclination magnetization which persists up to  $500^\circ\text{C}$ . Random, well-defined convergent directions are then displayed up to  $600^\circ\text{C}$ . IRM acquisition spectra show saturation by about 200 mT, indicating the dominance of a low coercivity mineral such as magnetite (Figure 3.3C). Stepwise thermal demagnetization of a tuff breccia at site 9102 shows removal of a well-grouped magnetization up to about  $500^\circ\text{C}$ , where random magnetizations are revealed. This behavior is interpreted to indicate that this tuff breccia was emplaced at about  $500^\circ\text{C}$  and captured a thermal remanent magnetization (TRM) as it then cooled. Site 9125 shows a less well defined intermediate temperature magnetization and the same criteria as for site 9102 suggest emplacement at about  $400^\circ\text{C}$ .

Table 3.1 displays paleomagnetic results for the formation of Troy Peak. Data of Ross (1988) from basalt flows in the southwest Cady Mountains are averaged with results from this study (Table 3.1). Directions from all sites have been corrected using

Table 3.1 - Paleomagnetic Data from the Formation of Troy Peak

Site	Bedding	Location Lat/Long	Nd/Ng/ Nt	In Situ Dir. Dec/Inc	$\alpha_{95}$	k	Fold Corrected Dir. Dec/Inc <sup>f</sup>
<b>North Limb</b>							
9033	220/42	34.848/-116.531	5/0/7	318.6/16.0	4.9	243.6	313.6/-25.5
9034	220/42	34.848/-116.531	6/0/6	322.2/11.5	7.2	87.6	318.2/-29.5
9033/9034*	220/42		11/0/13	320.6/13.6	4.3	114.9	316.1/-27.7
9035	220/42	34.848/-116.531	7/0/7	347.3/-3.5	3.5	291.4	352.2/-35.2
9036	220/42	34.848/-116.531	6/0/7	329.8/0.0	4.5	226.1	330.3/-39.0
9037	220/42	34.848/-116.530	5/0/6	317.8/5.2	5.4	205.4	314.1/-36.4
9038	220/42	34.849/-116.530	6/0/9	319.0/3.0	14.5	22.2	316.0/-38.4
9037/9038*	220/42		11/0/15	318.4/4.0	7.3	40.4	315.1/-37.5
9125	241/50	34.847/-116.530	4/3/10	320.4/2.2	15.8	22.8	307.7/-46.7
Mean			5/0/5	147.3/-3.3	13.0	28.6	
					14.8	22.1	144.5/38.3
WC1†	208/42	34.863/-116.550	10/0/11	304.7/-1.2	8.8	28.0	302.5/-42.8
WC2†	253/55	34.857/-116.527	6/0/7	300.4/-2.0	4.0	285.2	274.3/-38.5
WC3†	243/36	34.854/-116.503	4/0/6	297.4/-16.4	9.9	87.6	277.3/-43.4
Mean of North			8/0/8	137.4/0.4	12.0	17.0	
Limb					14.4	13.7	130.1/41.4
<b>South Limb</b>							
9102	137/39	34.831/-116.548	7/6/8	297.3/-16.1	12.2	17.0	314.4/-24.8
9103	103/26	34.825/-116.504	7/0/7	242.4/-31.9	11.3	29.5	263.9/-45.8
9104^	103/26	34.825/-116.504	9/0/10	161.2/27.6	26.4	4.8	168.3/04.9
9105	103/26	34.825/-116.503	7/0/10	257.4/-35.5	14.9	17.4	262.3/-37.9
Mean			3/0/4	086.9/30.0	44.0	5.9	
					42.4	6.3	102.1/38.9
WC4†	138/30	34.835/-116.553	7/0/7	255/-52.4	8.8	48.3	304.6/-73.3
WC6†^	084/30	34.743/-116.502	7/0/11	355.3/6.4	5.7	113.4	000.0/36.4
WC7†	090/06	34.824/-116.531	9/0/10	304.4/-67.8	8.2	40.4	315.6/-64.0
WC8†	090/06	34.825/-116.531	7/0/7	279.5/-50.2	8.1	56.6	287.2/-48.9
WC9†	090/06	34.827/-116.532	4/0/7	295.8/-49.2	5.1	326.3	302.4/-46.3
Mean of South			7/0/9	094.0/45.6	18.6	9.9	
Limb					16.8	11.9	111.1/50.7
Mean of Troy			15/0/17	121.5/22.4	18.6	5.2	
Peak Sites					10.7	12.8	122.1/46.1

\* = cooling unit average used in mean calculation, ^ = anomalous direction not included in mean

† = direction reported in Ross (1988), <sup>f</sup> = corrected for antiform plunging 17°/250.

the gently plunging fold determined by field observations. Correction for the plunging fold (Figure 3.4B, C; Table 3.1), gives a positive fold test at the 95% confidence level (cf. McElhinney, 1964;  $k_2/k_1 = 2.46$ ; 95% limit = 1.88). For the fold test of McFadden (1990),  $\xi_2$  (11.821) exceeds the critical value at 99% (6.3) for *in situ* coordinates indicating correlation of directions with tectonic position. For tectonic corrected coordinates,  $\xi_2$  (4.049) is less than the critical value at 95% (4.5) providing no reason to preclude the notion that acquisition of these magnetizations occurred prior to folding (McFadden, 1990). The age of folding is poorly constrained, however, interpreted to have occurred sometime younger than 14 Ma. Site inclinations move close to the expected Miocene inclination with application of the tectonic correction, indicating that the assumption of original horizontality is realistic. The characteristic magnetizations of the formation of Troy Peak are interpreted to be primary TRMs due to the high magnetization intensity values of the basalts, secular variation and positive fold test.

### **Formation of Poe**

One hundred sixty-seven samples were collected from 30 sites from volcanic breccias, tuffs and flows of the formation of Poe. Sixteen sites display either well defined yet random magnetizations (probably deposited as cold lahars or breccias) or complicated multi-component behavior (possibly due to partial remagnetization of these rocks associated with formation of Troy Peak volcanism) and thus are not used for tectonic analysis. The other sites show well-grouped magnetizations (Table 3.2) and the interpretation of these is discussed below in groups according to their characteristics.

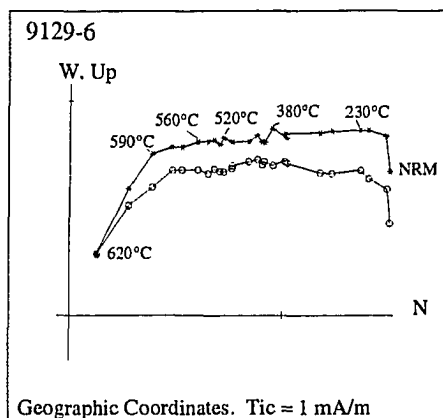
**Secondary magnetizations.** Samples from sites 9129, 9009 and 9014 display similar magnetization characteristics. These samples show a rapid rise in IRM up to inductions of 300mT and a slow rise in IRM with higher treatment, indicating a

Table 3.2 - Paleomagnetic Data from the Formation of Poe

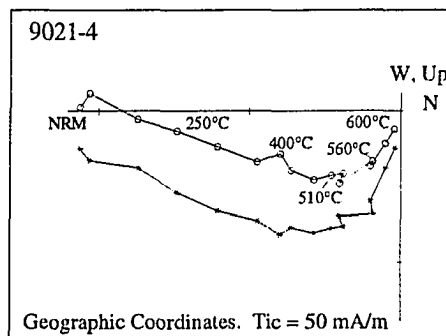
Site	Bedding	Location Lat/Long	Nd/Ng/ Nt	In Situ Dir. Dec/Inc	$\alpha_{95}$	k	Fold Corr. Dir. ^	Fold +Tilt Corr. Dir. ^
9024 <sup>P</sup>	275/39	34.844/-116.522	5/6/9	350.6/-12.2	17.4	11.7	358.0/-40.8	328.0/-49.5
9020/21 <sup>R</sup>	233/50	34.844/-116.534	3/6/8	110.4/32.6	14.6	22.8	078.7/62.6	051.2/62.8
9019 (High T) <sup>P</sup>	233/50	34.843/-116.533	2/4/4	346.9/21.7	19.2	25.4	339.9/-10.6	340.4/-24.5
9019 (Low T)	233/50		4/4/4	246.0/9.4	3.1	462.5	242.5/-4.2	241.5/-3.7
9018 (High T) <sup>P</sup>	233/50	34.843/-116.532	3/5/8	299.1/5.2	26.1	9.1	291.3/-30.1	284.2/-39.8
9018 (Low T)	233/50		4/5/8	258.5/2.5	6.7	94.0	249.2/-16.8	244.9/-17.5
9124 <sup>P</sup>	233/50	34.843/-116.532	8/8/8	290.7/-0.3	9.0	25.5	280.1/-33.2	271.1/-40.6
9123 <sup>P</sup>	218/50	34.842/-116.531	2/6/8	306.7/-22.4	24.0	11.4	294.2/-58.6	301.1/-72.4
9015 <sup>P</sup>	218/50	34.842/-116.530	7/0/8	307.9/-25.7	1.9	997.0	295.2/-62.0	304.5/-75.6
9014 <sup>R</sup>	218/50	34.842/-116.530	4/6/8	317.0/-42.8	13.9	21.7	315.0/-79.8	60.2/-82.8
9115 <sup>A</sup>	218/50	34.842/-116.530	6/8/8	012.2/-9.2	13.1	15.3	18.2/-27.3	25.2/-25.7
9114 <sup>A</sup>	220/60	34.841/-116.530	3/7/7	041.0/63.6	8.5	67.8	348.7/43.8	336.9/27.3
9009 <sup>R</sup>	220/60	34.841/-116.530	5/6/10	331.6/-33.0	7.9	51.9	346.3/-67.1	50.7/-71.6
9007 (High T) <sup>P</sup>	220/60	34.842/-116.527	4/4/4	279.2/4.4	16.6	18.1	269.7/-24.8	261.0/-44.3
9007 (Low T)	220/60		4/4/4	260.0/1.4	12.0	33.5	250.0/-18.5	241.1/-32.7
9129 <sup>R</sup>	220/60	34.841/-116.528	3/5/8	308.5/-37.6	8.8	71.3	289.2/-73.7	137.7/-82.7
Mean of Poe			n=7	130.7/4.6	25.1	5.8	123.8/41.4	
Primary					21.2	7.7		118.4/53.4
Mean of Poe			n=4	131.8/37.5	17.0	22.6	118.4/74.2	
Secondary					22.8	12.9		325.1/87.8
Poe secondary +			n=19	123.7/26.1	14.8	6.1		
Troy Peak					10.0	12.2	121.7/52.1	

P, R and A refer to presumed primary, remagnetized and anomalous directions, respectively.

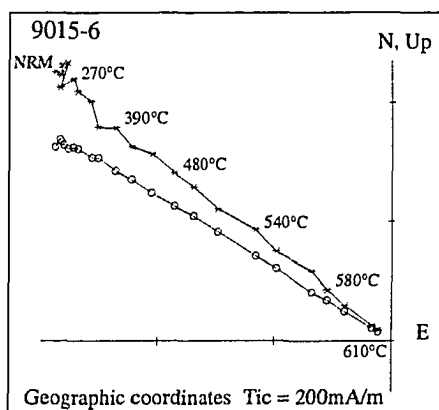
^ = Corrected for an antiform plunging 17°/250° and bedding of 226°/37°N.



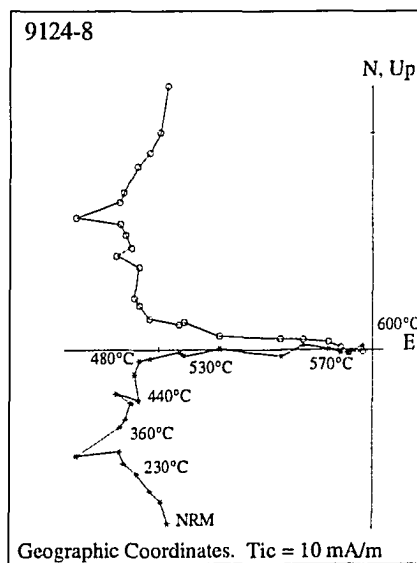
3.5A



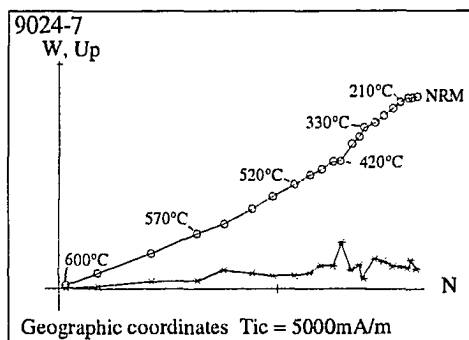
3.5B



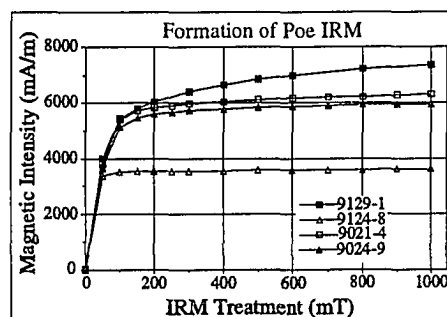
3.5C



3.5D



3.5E



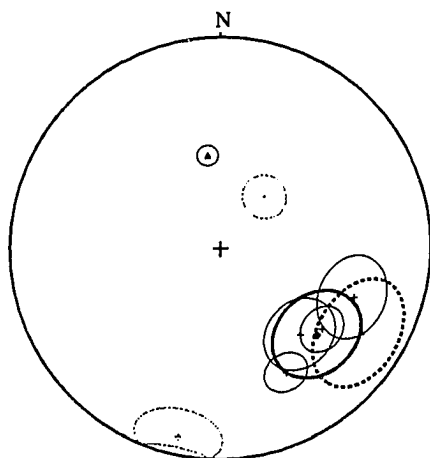
3.5F

Figure 3.5 Paleomagnetic diagrams from the formation of Poe. Circles lie in the vertical plane and stars in the horizontal plane. Thermal demagnetization diagrams show remagnetized high unblocking temperature components in A) (9129-6, reworked tuff) and B) (9021-4, volcanoclastic breccia), with a stable, convergent primary direction shown in C) (9015-6, fine surge deposit), D) (9124-8, massive tuff) and E) (9024-7, andesite flow). IRM acquisition spectra shown in 3.5F, are from sister cores or samples to the samples in A, B, D and E. The spectra show the dominance of a low coercivity component in samples 9124-8 and 9024-9 and the appearance of a high coercivity component in samples 9129-1 and 9021-4.

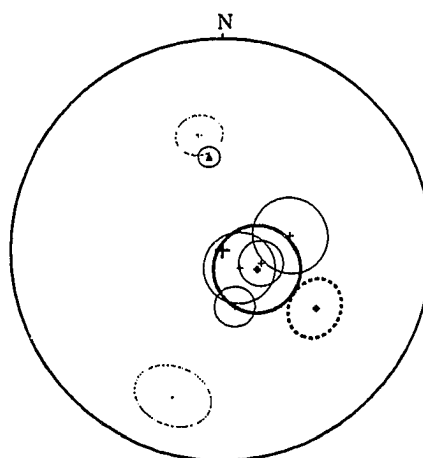


dominance of a low coercivity phase, but the presence of a higher coercivity phase (Figure 3.5F). Stepwise thermal demagnetization shows distributed unblocking temperatures, indicating that the dominant magnetic carrier is magnetite, with a component of hematite or maghemite (Figure 3.5A). A clear negative inclination magnetization is unblocked above 600°C and is carried by hematite or maghemite. Samples from sites 9020 and 9021 show a southeast and positive inclination, high unblocking temperature magnetization (Figure 3.5B). Data from the two sites have been averaged together because of their spatial proximity, lithological similarity and consistent paleomagnetic behavior. These samples show a rapid rise in IRM up to 100 mT followed by a gradual rise in IRM which does not reach saturation by 1T indicating the dominance of a low coercivity magnetic phase with the presence of a high coercivity phase (Figure 3.5F). Unblocking temperatures above 590° C indicate that hematite or maghemite carries at least a portion of the characteristic component.

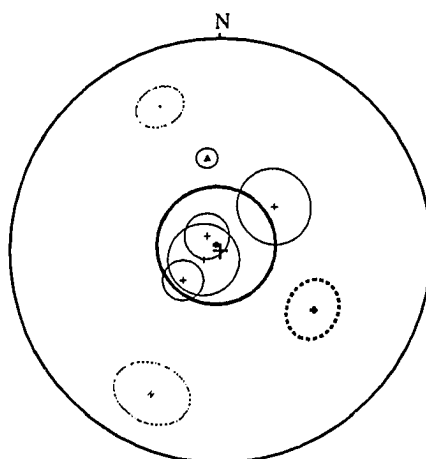
All of these sites plot very close to the mean direction for the formation of Troy Peak (with the site 9020/9021 magnetization antipodal) both before and after correction for the plunging anticline (Figure 3.6A, B). However, when the initial bedding tilt is removed, the magnetizations of these sites move to highly anomalous directions, typically with inclinations greater than 70° and a change of declination quadrant, suggesting that these magnetizations were acquired after initial tilting of the formation of Poe strata (Figure 3.6C). Because the characteristic magnetization in each of these sites is carried by hematite or maghemite and the directions are close to the mean direction for the formation of Troy Peak, these magnetizations are interpreted to be secondary, acquired near the time of eruption of the formation of Troy Peak basalts. These data are combined with the results for the formation of Troy Peak because of their uniformity and the likelihood of having acquired characteristic magnetizations near the same time (Table 3.2).



3.6A Formation of Poe, Secondary In Situ Coordinates



3.6B Formation of Poe, Secondary Fold Corrected



3.6C Formation of Poe, Secondary Fold and Tilt Corrected

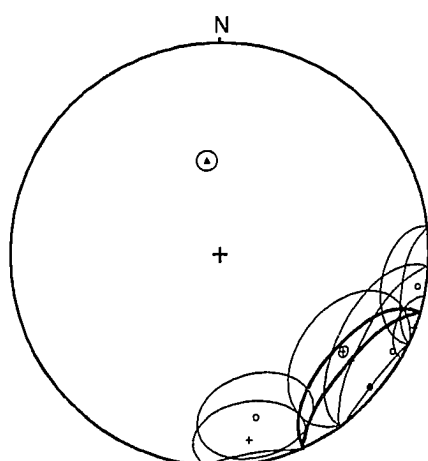
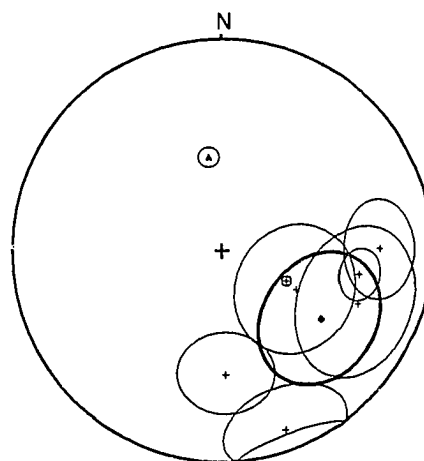
Figure 3.6. Secondary and anomalous paleomagnetic directions of the formation of Poe. Equal area lower hemisphere projection with 95% confidence ellipses and referred to normal polarity. The solid triangle is Miocene normal polarity reference direction calculated from Deihl and others (1983), the heavy dashed line is the mean direction of the formation of Troy Peak. Mean directions are in heavy line, "anomalous" sites are in thin broken line. These directions are shown for in situ coordinates (A.), after correction for the SW plunging anticline (B.) and after subsequent removal of tilt of bedding about strike (C.) as explained in text.

**Anomalous magnetizations.** Samples from sites 9114 and 9115 have high unblocking temperature magnetizations with northeast and down and northeast and shallow up directions, respectively (Table 3.2; Figure 3.6A). These sites give highly anomalous data and tectonic correction of these magnetizations for both folding and tilt of bedding does not move their inclinations near that of the expected direction, suggesting that these directions do not represent an axial geocentric dipole field direction. These data are excluded from tectonic interpretations because of their anomalous magnetizations.

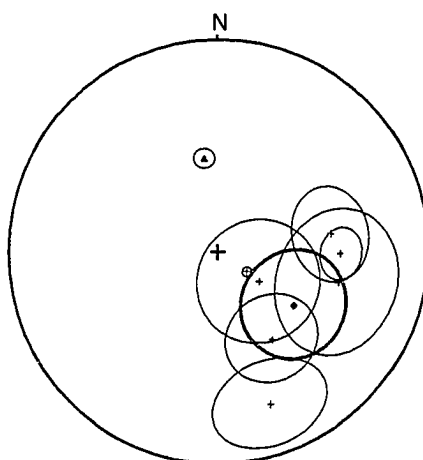
**Primary magnetizations.** Samples from sites 9007, 9015, 9018, 9123, 9124, 9019 and 9024 give a low unblocking temperature, present field overprint. For sites 9007, 9018 and 9019, two additional magnetizations are separated using principal component analysis (Kirschvink, 1980). The higher unblocking temperature magnetization is interpreted to be the primary characteristic magnetization in each case due to its demagnetization behavior and restoration of the inclination to expected values upon application of tectonic corrections. Unblocking temperatures indicate that the characteristic magnetizations for sites 9007, 9018 and 9019 are carried by both magnetite and hematite (or maghemite). Site 9015 gives an extremely well-grouped, convergent magnetization that has a northwest declination and a negative inclination (Figure 3.5C). Site 9123 shows effects of a strong present field overprint, so 2 characteristic directions and 7 demagnetization planes were combined to yield a northwest and up site mean. The characteristic magnetization from site 9123 is held to above 590° C indicating hematite or maghemite as a carrier which agrees with a high coercivity phase identified by a slow rise in IRM between inductions of 300mT and 1T. Site 9124 displays a convergent characteristic magnetization after removal of a low unblocking temperature overprint (Figure 3.5D). A rapid rise in IRM with saturation at 300mT indicates the dominance of a low coercivity phase (Figure 3.5F). Stepwise

thermal demagnetization reveals unblocking temperatures below 580° C suggesting that magnetite is the magnetic carrier for the characteristic magnetization. Samples from site 9024 display a well-grouped, convergent characteristic magnetization (Figure 3.5E). An initial rapid rise in IRM to 300mT suggests the dominance of a low coercivity phase with a slight rise up to inductions of 1T, indicating that a high coercivity phase is also present. Stepwise thermal demagnetization indicates that 10% of the NRM intensity remains after 590° C, which is consistent with magnetite and a small amount of hematite as carriers of the magnetization.

Site mean data from sites 9007, 9015, 9018, 9123, 9124, 9019 and 9024 lie well away from the present earth's magnetic field and present dipole field directions in *in situ* coordinates (Table 3.2, Figure 3.7A). After removing effects of folding, most sites have considerably shallower inclinations than expected for Miocene values (Figure 3.7B). The exceptions are sites 9015 and 9123 which display moderate inclinations. After correction for the pre-formation of Troy Peak tilt of bedding, the formational mean moves closer to the expected inclination and the dispersion in site means decreases (Figure 3.7C). The comparison does not pass the McElhinney (1964) fold test and shows indeterminate results with the McFadden (1990) test. Kappa values computed from inclinations alone (Kono, 1980) yield an *in situ* value of 13.5 and a bedding value of 115.2. When these kappas are compared using the methods of McElhinney (1964), a passing of the fold test at the 99% level is indicated ( $k_2/k_1=8.5>4.16$  for 99% level). Despite an inconclusive conventional fold test, the passing of an inclination only fold test, combined with the movement of the mean inclination toward the reference inclination upon application of tectonic corrections, indicates that these characteristic directions were probably acquired prior to early Miocene tilting and are may be primary directions acquired during cooling or deposition of these rocks.

3.7A. Formation of Poe *In Situ* Coordinates

3.7B. Formation of Poe Fold Corrected Coordinates



3.7C. Formation of Poe Fold and Tilt Corrected Coordinates

Figure 3.7. Primary paleomagnetic directions of the formation of Poe. Equal area lower hemisphere projections with 95% confidence ellipses and referred to normal polarity. The solid triangle is Miocene normal polarity reference direction calculated from Deihl and others (1983), mean directions are in heavy line. These directions are shown for in situ coordinates (A.), after correction for the SW plunging anticline (B.) and after subsequent removal of tilt of bedding about strike (C.) as explained in text.

### **"Barstow Formation"**

Twenty-three paleomagnetic sites (167 samples) were collected from lacustrine siltstones and tuffs in the middle Miocene "Barstow Formation". Hand samples were taken at nineteen sites with cores taken at a four sites where the outcrop was well indurated. Nine sites from the "Barstow Formation" do not provide adequate information to be used for the determination of tectonic rotation due to non-convergent and non-consistent magnetizations (possibly due to too large of grain size) and thus are not used in this study. Fourteen sites display well-grouped and convergent directions and are used in determination of tectonic rotation as discussed below and listed in Table 3.3.

Sites 9026, 9112, 9127 and 9030 show convergent reverse polarity magnetizations and sites 9027, 9119 and 9126 display convergent normal polarity magnetizations. A low unblocking temperature overprint is usually removed by 250° C to 300° C to reveal the characteristic magnetizations (Figures 3.9A, B). A rapid rise in IRM with treatment up to 300mT suggests the dominance of a low coercivity phase like magnetite and a gradual rise in IRM from 300mT to 1T indicates a high coercivity phase (Figure 3.8E). Stepwise thermal demagnetization reveals that the unblocking temperature of the characteristic magnetization ranges to above 600° C, indicating that these reverse polarity magnetizations are carried by both magnetite and hematite (Figures 3.9A, B). The mean direction for site 9119 is poorly determined due to a high number of samples with a persistent overprint, but the other sites give well determined mean directions (Table 3.3).

Site 9113 displays a strong normal polarity overprint, which, upon removal reveals a well defined reverse polarity magnetization between 230° and 450° C in each sample. Three samples show a reverse polarity, southwest declination and the

Table 3.3 - Paleomagnetic Data from the "Barstow Formation"

Site	Bedding	Location Lat/Long	Nd/Ng/ Nt	In Situ Dir. Dec/Inc	$\alpha_{95}$	k	Fold Corr. Dir. Dec/Inc#
9127	355/19	34.812/-116.502	7/0/8	183.0/-44.2	9.7	39.5	199.4/-38.8
9126	355/19	34.813/-116.503	7/0/8	022.7/ 60.4	6.0	101.9	043.9/ 48.4
9121 (High T)^	218/05	34.817/-116.500	8/8/8	008.4/ 66.2	3.6	151.4	358.9/ 63.4
9121 (Low T)	218/05	34.817/-116.500	8/8/8	237.7/-52.3	12.0	14.5	230.7/-53.7
9031	218/05	34.817/-116.500	7/0/8	208.0/-45.5	10.6	33.2	203.1/-44.4
9120 (High T)^	093/14	34.819/-116.499	7/7/7	026.6/ 52.3	5.6	71.6	039.7/ 64.6
9120 (Low T)	093/14	34.819/-116.499	5/7/7	206.2/-56.2	12.4	19.9	221.5/-68.4
9030*	093/14	34.820/-116.500	8/0/8	252.8/ 5.7	9.8	33.1	252.1/ 0.8
9029 (High T)^	093/14	34.820/-116.500	8/8/8	040.2/ 55.9	7.8	32.8	062.7/ 65.7
9029 (Low T)	093/14	34.820/-116.500	7/8/8	213.1/-40.0	6.3	55.5	225.4/-51.6
9119	090/22	34.821/-116.501	3/3/8	024.6/ 19.5	16.2	14.6	033.5/ 39.1
9118	070/33	34.821/-116.501	5/0/7	029.3/ 58.3	12.7	37.2	093.7/ 64.2
9117*	070/33	34.821/-116.501	4/0/6	032.3/-31.4	18.2	26.4	023.1/ -8.8
9027	095/31	34.822/-116.497	6/0/8	078.4/ 33.3	11.7	33.6	100.6/ 36.4
9113	095/31	34.822/-116.498	3/0/6	234.0/-25.2	14.9	69.7	252.0/-42.2
9112	095/31	34.822/-116.497	10/0/11	248.9/-35.2	5.6	74.9	274.2/-42.8
9026	096/44	34.822/-116.497	11/0/14	238.3/-11.9	17.1	8.3	255.9/-34.3
9108 (High T)	103/26	34.825/-116.503	4/0/7	043.2/42.0	12.6	54.1	065.8/ 62.0
9108 (Low T)^	103/26	34.825/-116.503	4/4/7	159.1/-30.8	17.3	16.9	147.2/-50.6
Mean, Normal Polarity			5/0/15	41.1/ 44.8	23.9	9.0	
					22.7	9.9	65.8/ 53.4
Mean, Reverse Polarity			8/0/15	43.1/ 40.7	15.6	11.9	
					14.8	13.0	53.9/ 49.9
Mean of Barstow Sites			15/0/15	044.3/ 35.2	15.3	6.7	
					14.4	7.5	056.2/ 44.9
Final Mean of Barstow Sites			13/0/15	042.4/ 42.3	11.6	12.6	
					11.2	13.5	058.3/ 51.4

^ and \* designate directions not used in calculation of mean directions and final mean direction, respectively. # = corrected for an antiform plunging 17°/250°

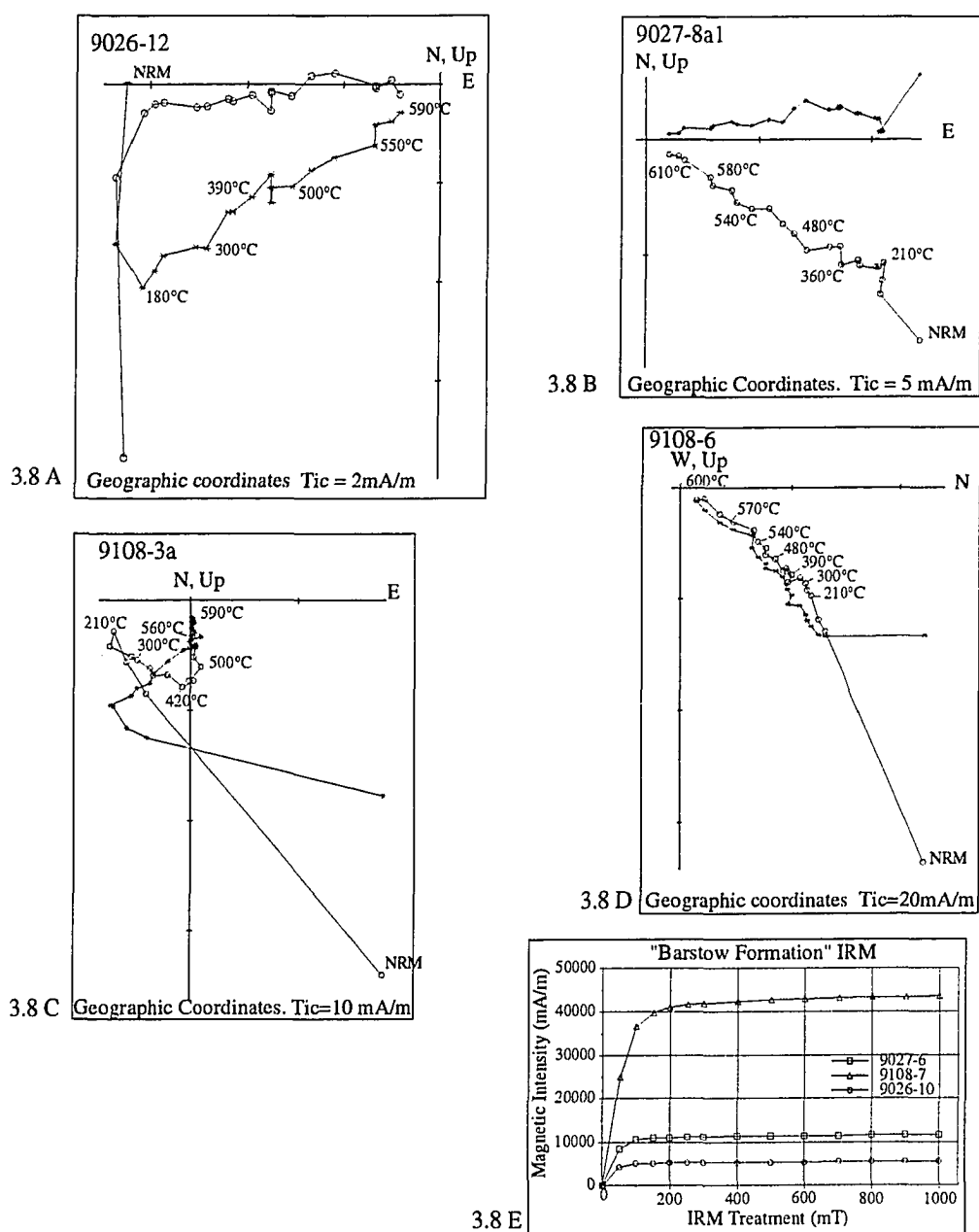
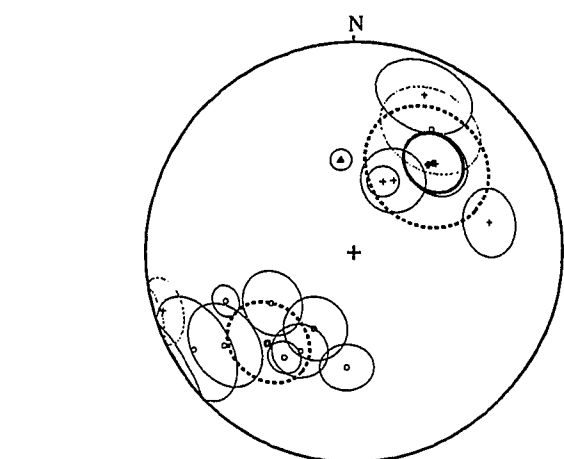


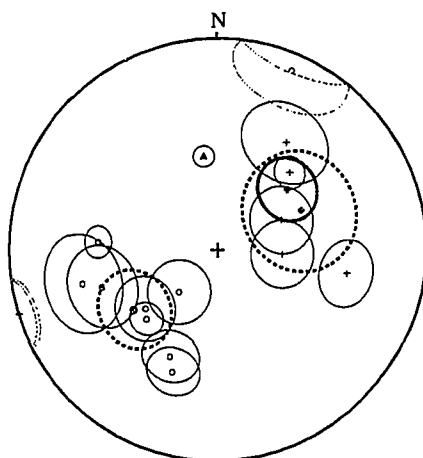
Figure 3.8. Paleomagnetic diagrams from the "Barstow Formation". Circles lie in the vertical plane and stars in the horizontal plane. Thermal demagnetization diagrams show stable, convergent components in A (9026-12, siltstone) and B (9027-8, tuff). Sample 9108-3 (C, tuff) displays a moderate unblocking temperature reverse component, whereas sample 9108-6 (D, tuff) does not appear to contain this component. The IRM acquisition spectra shown for samples 9027-6 and 9026-10 (E) display the dominance of a low coercivity component, whereas the spectra for sample 9108-7 suggests that a high coercivity component is also present.





3.9 A

"Barstow Fm." In Situ Coordinates



3.9 B

"Barstow Fm." Fold Corrected Coordinates

Figure 3.9. Paleomagnetic directions of the "Barstow Formation". Equal area projection with 95% confidence ellipses, + = lower hemisphere and o = upper hemisphere.. The solid triangle is Miocene normal polarity reference direction calculated from Deihl and others (1983), mean directions are in heavy line with mean directions of normal and reverse polarities in heavy shaded line. These directions are shown for in situ coordinates (A.) and after correction for the SW plunging anticline (B.) as explained in text.

remaining three have a reverse polarity, northwest declination. The reverse polarity, southwest magnetization is consistent with the data of surrounding sites and lies near the expected Miocene inclination after tectonic correction, whereas the reverse polarity, northwest magnetization shows an unreasonably shallow inclination after correction (Table 3.3). It is possible that two different beds were sampled at this locality, providing two separate magnetizations.

Site 9031 yields a low unblocking temperature, reverse polarity magnetization between 200° and 350° C. At higher temperatures, these samples display chaotic behavior with no convergent magnetization. Sites 9108, 9029, 9120 and 9121 reveal up to three distinct magnetic directions. Rapid IRM acquisition up to 200 mT suggests that a low coercivity phase, possibly magnetite, is the dominant carrier for these sites (Figures 3.8C, E). A low unblocking temperature, present field overprint is usually removed by 200° C to reveal a reverse polarity remanence between 200° and 450° C. After removal of this reverse polarity component, a normal polarity component is apparent (Figure 3.8C). The normal and reversed components at one site are either antipodal (9029 and 9120) or very different from each other (9108 and 9121; Table 3.3). Because these magnetizations typically have inclinations close to that of the Miocene reference direction after tectonic correction, it is difficult to assign a primary designation between them.

Two samples from site 9108 do not display a reverse component between 200° and 400°, and show convergent normal polarity directions after removal of the present field overprint (Figure 3.8D). The high temperature normal polarity component displayed by these samples is interpreted to be the primary magnetization. In site 9121, however, the normal polarity magnetization is close to the present field direction (*in situ* coordinates) and is interpreted to be a secondary magnetization. Sites 9029 and 9120 both display two nearly antipodal components, so choosing a primary magnetization from these

components is difficult, though the formational mean is not changed significantly by the decision. The age and underlying magnetostratigraphy suggest that these sedimentary rocks acquired a remanence in a dominantly reverse polarity chron, suggesting that the primary component may be of reverse polarity. For the above reasons, the low unblocking temperature reverse polarity magnetizations for sites 9121, 9120 and 9029 are used in calculating the formational mean; the high unblocking temperature normal polarity direction from site 9108 is used in calculation of the formational mean (Table 3.3).

Data from two sites (9030 and 9117) are excluded from the final mean direction for the "Barstow Formation" because their magnetization directions lie more than  $3\sigma$  from the formation average, have very low inclinations after tectonic correction, and are interpreted to have been acquired during a magnetic excursion or during a magnetic reversal. "Barstow Formation" sites display both magnetic polarities and the mean directions and values of kappa for normal and reverse polarity sites are not significantly different at the 95% confidence level, thus passing a reversal test. The final *in situ* mean paleomagnetic direction for the "Barstow Formation" is lower in inclination than expected, but becomes very close to the expected inclination after tectonic correction. The dispersion about the mean direction decreases after application of the tectonic correction (Figure 3.9; Table 3.3). Only one limb of the anticline is exposed containing "Barstow Formation" strata is exposed, rendering a formal fold test impossible. The inclinations moving closer to the Miocene reference value after fold correction and the positive reversal test suggest that these magnetic directions were acquired prior to folding of these strata.

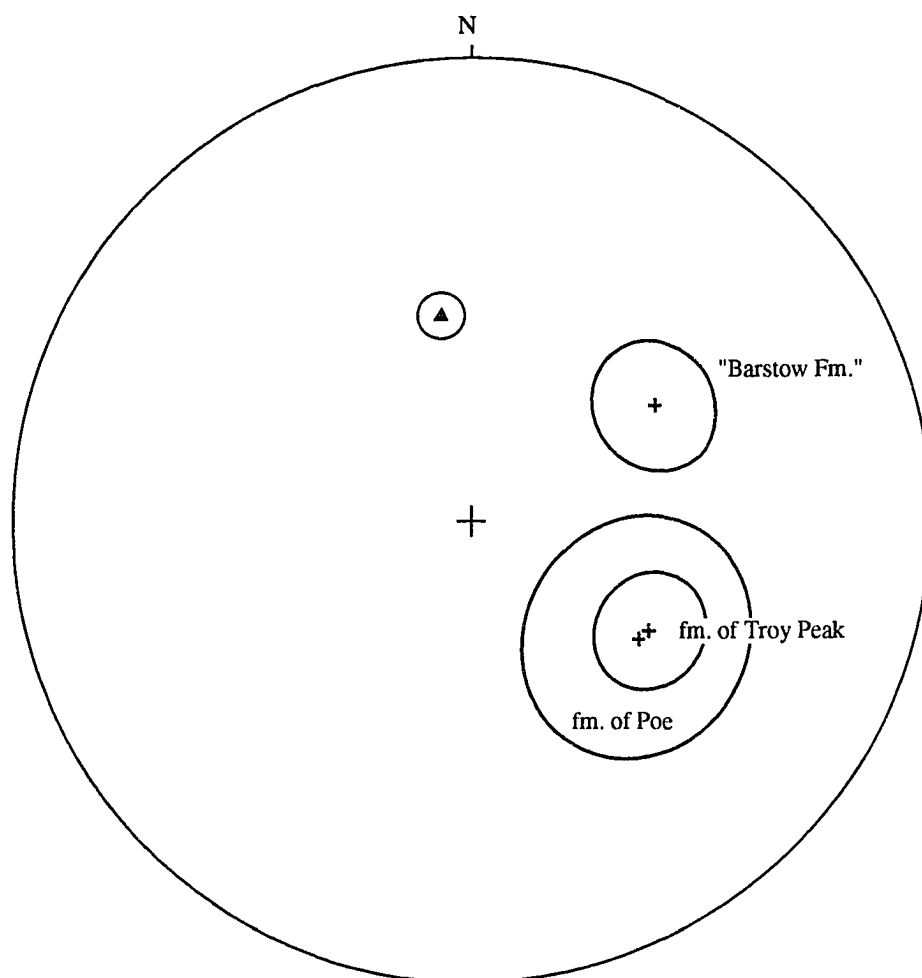
## DISCUSSION

### Summary of Paleomagnetic Data

The mean direction for sites of the formation of Poe ( $D=124.7$ ,  $I=53.1$ ,  $\alpha_{95}=20.8$ ) capturing primary magnetizations is based on seven site means which have inclinations which lie closer to the reference value after tectonic correction (Table 3.2). The formation of Troy Peak data are combined with secondary magnetizations from the formation of Poe to give a well determined mean direction that passes a fold test ( $D=121.7$ ,  $I=52.1$ ,  $\alpha_{95}=10.0$ ; Tables 3.1, 3.2). Data for the "Barstow Formation" ( $D=58.3$ ,  $I=51.4$ ,  $\alpha_{95}=11.2$ ) pass a reversal test and have inclinations close to the Miocene reference value after tectonic correction (Table 3.3).

The formational mean directions for the formation of Poe, formation of Troy Peak and "Barstow Formation" are distinct from either geographic north or the Miocene reference direction for this area (Figure 3.10). The formation of Poe primary directions are somewhat dispersed, with these rocks plagued by multiple magnetic directions per sample. However, sites 9124, 9015 and 9024 established in igneous rocks, display convergent demagnetization paths, and have magnetizations which are similar to those from other rocks of this formation. The site means of the formation of Poe are all reverse polarity, but the dispersion of the mean direction suggests that some secular variation has been averaged.

The formation of Troy Peak also contains only reverse polarity magnetizations, but including secondary magnetizations from the formation of Poe provides one normal polarity magnetization. Sites in the formation of Troy Peak are mostly from basalt flows which display well-grouped, convergent magnetizations. These high intensity magnetizations pass a fold test and are interpreted to be primary. The variation in reverse polarity directions from the sequence of basalt flows discussed above suggests



3.10. SW Cady Mountains Bedding Coordinates

Figure 3.10 Summary of paleomagnetic data. Mean paleomagnetic directions for the formation of Poe, formation of Troy Peak and the "Barstow Formation" with their 95% confidence ellipses. The solid triangle is Miocene normal polarity reference direction calculated from Diehl and others (1983). These formation means display the two distinct clockwise rotations as discussed in the text.

Table 3.4 - Southwest Cady Mountains Discordance Statistics

Unit	Corrected Direction (D/I/a95)	Reference Direction (D/I/a95)	R	$\Delta R$	F	$\Delta F$
Poe fm.	118.4/53.4/21.2	351.8/53.3/ 4.0*	126.6	29.6	-0.1	16.8
Troy Peak fm.	121.7/52.1/10.0	351.8/53.3/ 4.0*	129.9	14.0	1.2	8.5
"Barstow Fm."	58.3/51.4/11.2	351.8/53.3/ 4.0*	66.5	15.0	1.9	9.4
Troy Peak fm.	121.7/52.1/10.0	58.3/51.4/11.2^	63.4	19.6	1.6	11.9

\* Reference direction from Diehl and others, 1983.

^ Difference between Troy Peak Fm. and "Barstow Fm.", "Barstow Fm." as reference.

R,  $\Delta R$ , F,  $\Delta F$  are calculated according to Beck (1980) and Demarest (1983).

that some amount of secular variation has been averaged in this sequence of rocks. Data from the "Barstow Formation" show a positive reversal test and represent acquisition of magnetization over a long period of time, thus are interpreted to average secular variation. The mean directions from the formations of Poe and Troy Peak and the "Barstow Formation" are interpreted to average secular variation sufficiently for comparison with the Miocene reference direction (calculated from Diehl and others, 1983) and calculation of directional discordance in terms of rotation and flattening parameters of Beck (1980) as given in Table 3.4.

### **Interpretation of Vertical Axis Rotation**

The formation means from this study are all highly deflected from both geographic north and the Miocene reference direction. Mean directions from the formations of Poe and Troy Peak have clockwise declination anomalies of over  $120^\circ$  and the "Barstow Formation" data shows a declination anomaly of almost  $60^\circ$  clockwise. In numerous paleomagnetic studies, observed declination anomalies have been interpreted to have been caused by vertical axis rotation. If the formational means are interpreted in terms of vertical axis rotation, they suggest very large clockwise rotations of  $132.9^\circ \pm 28.8^\circ$ ,  $129.9^\circ \pm 14.0^\circ$  and  $66.5^\circ \pm 15.0^\circ$  for the formations of Poe and Troy Peak and the "Barstow Formation" (respectively). Declination anomalies, however, can also result from incorrect structural correction, from crustal rotation about an inclined axis, and from multiple crustal tilting events about different horizontal axes. In this study structural corrections are based strictly on geological relationships observed in the field area. As discussed below, these geologic relationships argue against rotation about inclined axes and multiple tilting events.

Chan (1988) demonstrated a relationship between the tilt of bedding, declination anomaly, and the plunge of the rotation axis. According to Chan's plots and

considering the maximum bedding dips ( $60^\circ$ ), the  $17^\circ$  plunge of the fold would contribute a maximum of about  $24^\circ$  to the declination anomaly (apparent rotation). This  $17^\circ$  plunge has been removed in the correction procedure and so should not contribute to the apparent rotation of these rocks. An error in the plunge of  $5^\circ$  would add less than  $5^\circ$  to the declination anomaly. Because the maximum tilt of bedding combined with the plunge of folding cannot explain the full declination anomaly ( $25^\circ$  vs  $60^\circ$  to  $130^\circ$ ), these anomalous declinations cannot be explained by a single rotation about an inclined axis.

The "Barstow Formation" was deposited conformably on the formation of Troy Peak and contains fine grained lacustrine rocks most likely deposited near the horizontal datum. The application of tectonic corrections brings the mean for the formation of Troy Peak to within  $1.2^\circ$  (Table 3.4) of the Miocene reference value, suggesting that those rocks were also emplaced near horizontal. It is, therefore, highly unlikely that any multiple tilting events occurred between deposition of the formation of Troy Peak and deposition of the "Barstow Formation", yet the occurrence of a tectonic event is indicated by differences in the formation mean directions. The "Barstow Formation" is fairly shallowly dipping and also has probably not experienced multiple tilting events, though this is possible. Declination anomalies of the formations of Poe and Troy Peak and the "Barstow Formation" may reflect a rotation about a vertical axis and not to rotations about inclined axes or tilting events. The net vertical axis rotation for each unit has been quantified (Table 3.4) using the methods of Beck (1980) and Demarest (1983).

The difference in declination between the "Barstow Formation" and the formation of Troy Peak suggests that  $63^\circ \pm 19^\circ$  of clockwise rotation occurred after deposition of the formation of Troy Peak basalts ( $>21$  Ma), but before deposition of the "Barstow Formation" ( $\sim 16.5$  Ma; Figure 3.9; Table 3.4). This estimate of clockwise rotation is statistically indistinguishable from the  $49^\circ \pm 20^\circ$  clockwise rotation reported for the surrounding mountain ranges by Ross and others (1989). In addition, the estimate for



timing of rotation is similar (~21-16.5 Ma vs. ~23-18.3 Ma), suggesting that this pre-"Barstow Formation" rotation is a regional tectonic event. Paleomagnetic data from the "Barstow Formation" suggest that the southwest Cady Mountains rotated  $67^{\circ} \pm 15^{\circ}$  clockwise at some time after 14.0 Ma. There is not an obvious trend in declination versus stratigraphic position which would be expected if rotation was occurring coincident with deposition, so two separate clockwise rotations are interpreted from these data.

The above paleomagnetic data and their anomalous declinations are interpreted to have been caused by vertical axis tectonic rotations of the earth's crust. We propose two separate clockwise rotations of different age to explain the  $\sim 130^{\circ}$  of rotation of the formations of Poe and Troy Peak and the  $\sim 66^{\circ}$  of rotation interpreted from the "Barstow Formation" data. Two questions concerning the relationship between early Miocene extension and rotations in the southwest Cady Mountains can be addressed by combining the above paleomagnetic data with geologic field information. A tectonic history for the southwest Cady Mountains can then be formulated.

### **Rotation Associated With Extensional Tilting**

Field relationships indicate that tilting of strata associated with extension in the southwest Cady Mountains occurred prior to the deposition of the formation of Troy Peak. By comparing paleomagnetic data from the formation of Poe with those of the formation of Troy Peak, the hypothesis of vertical axis rotation concurrent with extension may be addressed. Paleomagnetic data for the formation of Poe suggest that the net clockwise rotation of about  $133^{\circ} \pm 29^{\circ}$  has affected those rocks, whereas data from the formation of Troy Peak suggest  $130^{\circ} \pm 14^{\circ}$  of clockwise rotation (Table 3.4, Figure 3.9). The two results are not statistically distinguishable and are interpreted to indicate that no rotation took place between deposition of the Poe beds and Troy Peak

beds. The formation of Poe strata were tilted by early Miocene extension prior to deposition of the formation of Troy Peak, thus the paleomagnetic data indicate that no rotation of the southwest Cady Mountains took place concurrent with this early, pre-Troy Peak phase of extension.

### **Direction of Early Miocene Extension in the Southwest Cady Mountains**

A normal fault dipping steeply to the SE and a strike-slip transfer zone striking NW-SE (Figure 3.2) suggest that the early Miocene extension direction in the southwest Cady Mountains is presently oriented NW-SE (Dokka and others, 1991; Ross and others, 1991). In order to establish the original orientation of extension, the rotations of the rocks overlying the formation of Poe must be removed. Removal of 67° of post 14 Ma clockwise rotation moves these structural elements in the southwest Cady Mountains to indicate a NE-SW directed extension (*i.e.*, dip direction of normal faults and strike of transfer faults to NE; dip direction of bedding to SW). Removal of this rotation aligns the extension direction for the southwest Cady Mountains sub-parallel to the present orientation of kinematic indicators in the rest of the Daggett extensional terrane (orientations of normal faults, slicken striae, and transfer boundaries NE-SW; Dokka, 1986, 1989). Paleomagnetic data from the formation of Troy Peak basalts rotate counterclockwise with this reconstruction to a position indicating about 63° of clockwise rotation, sub-parallel to other paleomagnetic data from the Daggett terrane (Ross and others, 1989). To achieve the original orientation of the tilted formation of Poe beds immediately post-extension, The remainder of the rotation of the formation of Troy Peak must be removed. Thus, when a net 130° of clockwise rotation is removed, structures and kinematic indicators for early Miocene extension in the southwest Cady Mountains are oriented ~N-S.

Similarities between the geology, structures and kinematic relationships of the southwest Cady Mountains and those of the Daggett terrane, as well as the Mojave extensional belt, allow these interpretations concerning extension and vertical axis rotation to be extended to much of the Mojave region.

### **Regional Early Miocene Extension Direction**

Kinematic indicators of the regional extensional direction in upper plate rocks are fault slip indicators (fault striae and fibrous mineral orientations) on normal faults in the Newberry and Cady Mountains and the orientation of the transfer zone between the Daggett and Bullion terranes (Dokka, 1986, 1989; Dokka and Woodburne, 1986). These data are supported by consistent dip directions of early Miocene strata within each terrane. The present orientation of these structures indicates that the Mojave extensional belt opened in a NE-SW direction (Dokka, 1986, 1989; Dokka and Woodburne, 1986; Bartley and others, 1990; Bartley and Glazner, 1991). Kinematic indicators from ductile lower plate rocks consist of well defined, NE-SW stretching lineations in mylonites which crop out in the Waterman Hills, Mitchel Range, Harper Lake and Hinkley Hills areas (Dokka and Woodburne, 1986; Glazner and others, 1988; Dokka, 1989; Bartley and others, 1990). These data consistently indicate a NE-SW extensional direction for all terranes and both upper and lower plate rocks.

All hypotheses proposed to account for early Miocene rotation in the Mojave Desert block, except that of Dokka (1989), have suggested that only upper plate rocks have rotated (Ross and others, 1989; Bartley and Glazner, 1991; Valentine and others, 1993). If only upper plate rocks experienced rotation, their extension directions should differ (by  $\sim 50^\circ$ ) from extension directions implied by kinematic indicators in the lower plate. The data do not support such models, as extension directions are the same for both upper and lower plate rocks. Because critical field and paleomagnetic relationships

in the southwest Cady Mountains indicate an original early Miocene extension direction oriented ~N-S, this implies that the original extension direction for the Mojave extensional belt was oriented ~N-S and that much of the Mojave Desert block experienced ~50° of clockwise rotation during early Miocene time.

### **Causes of Rotations**

**Pre-"Barstow Formation" regional rotation.** Investigations in the southern Sierra Nevada (adjacent to the Mojave Desert block to the west) indicate a Neogene oroclinal bending of at least portions of that area. Paleomagnetic studies by Kanter and McWilliams (1982), McWilliams and Li (1985) and Plescia and Calderone (1986) show that the southern tip of the Sierra Nevada was rotated clockwise up to 45° between ~24 Ma and 16 Ma. This rotation does not reach far enough north or northeast to affect the Independence dikes in the central Sierra Nevada. Burchfiel and Davis (1981) suggested that this orocline continues into the Mojave Desert block, and Golombeck and Brown (1988) interpreted the same tectonic event to have resulted in clockwise deflected declinations which they observed in 21 Ma volcanic flows in the Kramer Hills (Figure 1). Valentine and others (1993) have interpreted this oroclinal event to have also affected late Oligocene to early Miocene rocks in the northern central Mojave desert block. Because the regional rotation inferred for the central Mojave Desert (Ross and others, 1989; this study) and the southern Sierra Nevada are the same sense and approximately the same age and amount, these two rotations may be part of the same tectonic event.

The boundaries of early Miocene large-magnitude regional clockwise rotation in the Mojave Desert block have not yet been defined. The consistency in orientation of structural elements suggests that the entire Mojave Extensional Belt was affected by this clockwise rotation. There is a great likelihood that much of the Mojave Desert block

was affected also. However, the nature and cause of this regional tectonic rotation remains cryptic.

**Post-"Barstow Formation" rotation of the southwest Cady Mountains.** Paleomagnetic evidence for this young (<14 Ma) rotation is not found in any of the surrounding mountain ranges. This rotation is interpreted to be a local phenomenon associated with right-lateral movement on the Calico and Pisgah faults. The southwest Cady Mountains is envisioned to have rotated clockwise in a pinball fashion as slip accumulated on this fault system (Ross, 1991; 1992). Because these faults are still active, this area is probably still rotating.

## CONCLUSIONS

Paleomagnetic data from Miocene strata suggest that two separate clockwise vertical axis rotations have affected the southwest Cady Mountains. Directions from fluvial and lacustrine sediments of the "Barstow Formation" pass a reversal test and suggest that this area has rotated  $67^{\circ} \pm 15^{\circ}$  clockwise since 14.0 Ma. Data from stratigraphically older basalt flows of the formation of Troy Peak pass a fold test and suggest  $130^{\circ} \pm 14^{\circ}$  of clockwise rotation since their deposition. These basalts unconformably overlie tilted and extended lower Miocene strata of the formation of Poe, demonstrating that rotation of the basalts post-dates extension in the southwest Cady Mountains. Paleomagnetic data for the formation of Poe suggest that  $133^{\circ} \pm 29^{\circ}$  of clockwise rotation has affected these rocks after their deposition. The data from the formations of Poe and Troy Peak are statistically the same, indicating that clockwise rotation was now coincident with tilting due to extension in the southwest Cady Mountains. Restoring early Miocene structural elements to their pre-rotation configuration allows interpretation of the original extension direction for the southwest Cady Mountains to be oriented ~N-S.

Rocks of the southwest Cady Mountains are part of the Daggett extensional terrane and share similar early Miocene strata and geologic relationships with rocks of surrounding mountain ranges in the terrane. The orientation of faults and the dip of bedding of early Miocene strata in the southwest Cady Mountains indicate an extension direction much different than that of surrounding ranges. Paleomagnetic data from the southwest Cady Mountains indicate that rotation occurred after tilting due to extension. Removal of  $67^\circ$  of post-14 Ma clockwise rotation aligns extensional structures and associated kinematic indicators and paleomagnetic directions of the southwest Cady Mountains with their counterparts of the early Miocene Mojave extensional belt. The consistency of extensional kinematic indicators in the Mojave extensional belt implies that upper plate rocks have not rotated with respect to lower plate rocks. These relationships indicate that a vertical axis rotation must have affected the entire extensional belt and is, therefore representative of a separate major regional tectonic event.

Taken collectively, the above relationships indicate that the Mojave extensional belt experienced early Miocene, ~N-S directed extension, followed by about  $50^\circ$  of regional clockwise rotation. This rotation is interpreted to have affected the entire extensional belt as well as surrounding areas, and was not concurrent with what has now been demonstrated to be an earlier, major phase of regional extension as some previously proposed models require. These conclusions agree with the hypothesis of Dokka (1989) concerning an original N-S orientation of extension and support his thesis that early Miocene extension in the Mojave extensional belt was not directly related, kinematically or geometrically, to extension in the Colorado River extensional corridor.

## **CHAPTER 4 - THE ORIGIN OF EARLY MIOCENE REGIONAL ROTATION**

### **INTRODUCTION**

Recent paleomagnetic studies in the Mojave Desert and the southern Sierra Nevada of California imply that these regions have experienced substantial Neogene age vertical-axis rotation(s) (Figure 4.1). One series of models associates vertical-axis rotation with movement along the late Miocene to present NW striking dextral shear system through the Mojave Desert block (Garfunkel, 1974; Luyendyk and others, 1980; 1985; Carter and others, 1987; Dokka and Travis, 1990a). Another set of hypotheses attempts to explain early Miocene vertical-axis rotations by association with plate tectonic interactions (Kanter and McWilliams, 1982) or with early Miocene detachment-style extension (Ross and others, 1989; Bartley and Glazner, 1991; Valentine and others, 1993). Paleomagnetic data now exist which may distinguish between different ages of rotation and the possible mechanisms of producing these rotations.

A recent study by Ross (in review in Geological Society of America Bulletin [GSAB]; Chapter 3) utilizes paleomagnetic data and structural relationships in the southwest Cady Mountains to constrain the extent and timing of early Miocene clockwise rotation in the central Mojave Desert block. That study concludes that the rotation was regional in extent (larger than the boundaries of early Miocene extension) and occurred entirely after the major phase of early Miocene extension. Those conclusions imply that early Miocene extension was not the driving mechanism of rotation, and therefore, hypotheses invoking this mechanism to explain rotation are probably not valid. This paper investigates available data by which we may separate different episodes of vertical axis rotation in the Mojave Desert area and focuses on the

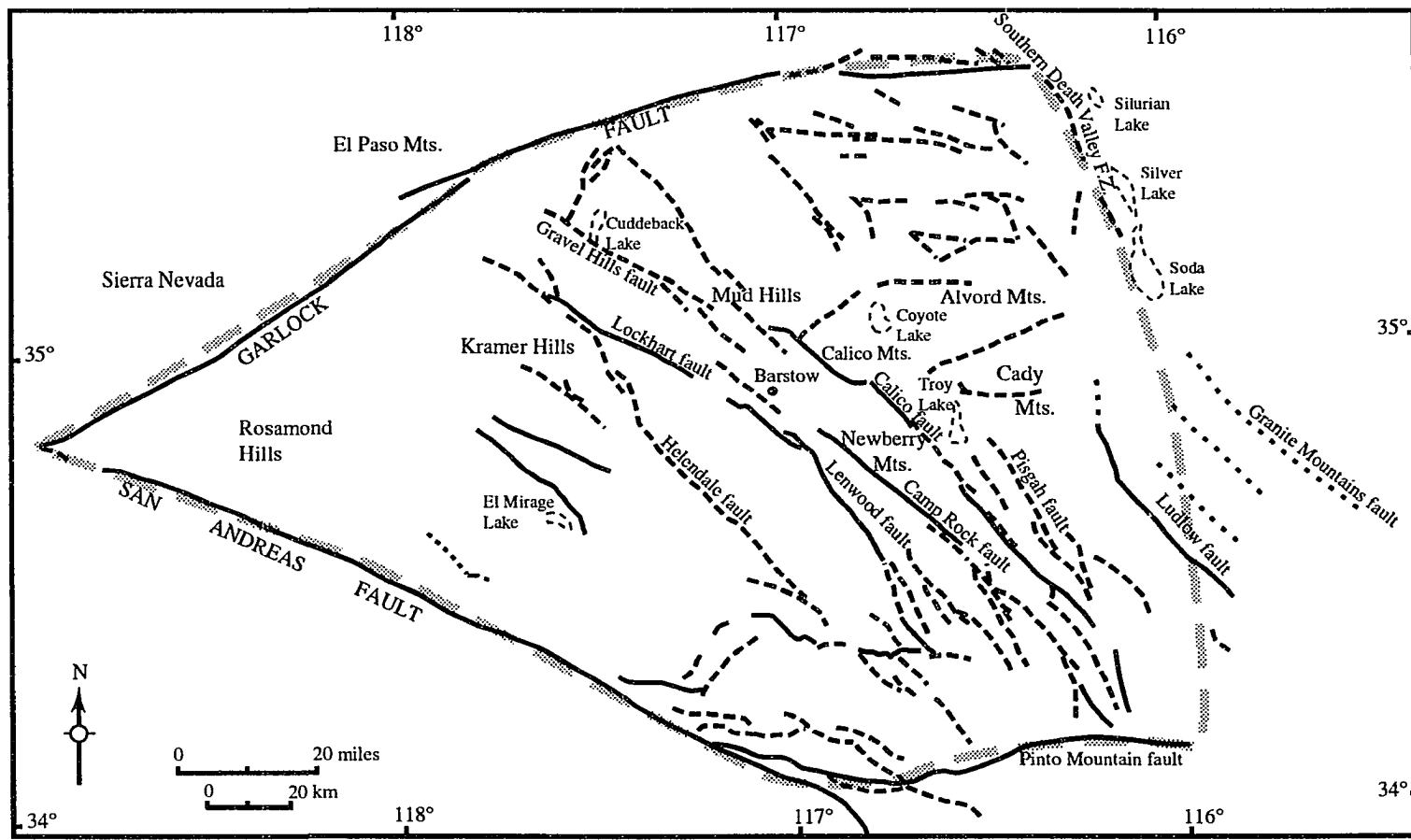


Figure 4.1 The Mojave Desert and surroundings. Approximate boundaries of the Mojave Desert block (cf. Dokka, 1983) are shown in grey dashed line.



problem of the existence, boundaries and one possible mechanism for producing early Miocene regional clockwise rotation in the Mojave Desert block and adjacent areas.

## **GEOLOGIC SETTING**

An episode of widespread volcanism swept through the Mojave region beginning in early Miocene time and continued activity through the mid-Miocene. This volcanism produced much of the pre- to syn-extensional deposits in the Mojave Desert block (Dokka, 1989; Travis, 1992). Early Miocene extension in the Mojave Desert block was accommodated by movement along normal-sense low angle detachment faults which locally exhumed rocks originating in the middle crust (Dokka 1986, 1989; Bartley and others, 1990; Henry and Dokka, 1992). Pressure-temperature-time path studies of these rocks show that they depressurized and cooled very rapidly from above 300°C to below 100°C at ~20 Ma (Dokka and others, 1991). As this extension progressed, upper plate rocks were faulted into crustal blocks and tilted about horizontal axes. Variability in rates and amounts of extension in the upper plate was accommodated along strike-slip transfer zones. The combination of shear orientations from mylonitic fabrics in the lower plate, and the orientation of transfer zones, the tilt direction of strata, and movement along normal faults in the upper plate all suggest a NE-SW extension direction (present coordinates). Recent paleomagnetic studies in the central Mojave Desert block indicate that ~50° of regional clockwise vertical axis rotation affected this area and is constrained to have occurred post extension, and prior to ~18.5 Ma (Ross, in review). The dextral Eastern California shear zone was established through the region after ~13 Ma (Dokka and Travis, 1990) and is thought to have facilitated late Miocene and younger local clockwise rotation in the NE Cady Mountains (MacFadden and others, 1990b), SW Cady Mountains (Ross and others, 1989; Ross in review) and the Alvord Mountains (Ross and others, 1989).

## REVIEW OF PALEOMAGNETIC STUDIES

Recent paleomagnetic studies from the Mojave Desert block and environs have produced an apparently confusing set of evidence for clockwise, counterclockwise, and null vertical axis crustal rotations in the Mojave Desert block. A variety of models have been invoked to explain these proposed rotations (Garfunkel, 1974; Luyendyk and others, 1980, 1985; Golombek and Brown, 1986; Bartley and Glazner, 1991; Valentine, in review). Before we undertake an analysis of these models, it is instructive to review the paleomagnetic data in detail to set forth the limits of our knowledge. A compilation of these studies is listed in Table 4.1 and a reference map is given in Figure 4.1. These data will be discussed in a rough progression from west to east.

### Southern Sierra Nevada

Paleomagnetic evidence for oroclinal flexure of the southern Sierra Nevada immediately west of the Mojave Desert block is presented in Kanter and McWilliams (1982), McWilliams and Li (1983, 1985) and Plescia and Calderone (1986). Kanter and McWilliams (1982) found that paleomagnetic directions from plutonic rocks of the 80-86 Ma Bear Valley Springs pluton are deflected clockwise from the Cretaceous reference direction and that overlying middle Miocene (~16 Ma) strata show no deflection from their reference direction. McWilliams and Li (1985) showed that this declination anomaly grows progressively larger toward the south, to a maximum of ~60° clockwise. Plescia and Calderone (1986) reported that (21-25 Ma) basalt flows of the Tecuya Fm. have been rotated  $40^{\circ} \pm 9.5^{\circ}$  clockwise since eruption. They proposed that ~40° of clockwise rotation of the southern Sierra Nevada took place between ~21 and 16 Ma.

Table 4.1 - Paleomagnetic Data Suggesting Neogene Rotations in and about the Mojave Desert.

Site	N	R	$\Delta R$	F	$\Delta F$	Age of Rotation	Reference
<b>Central Mojave Desert</b>							
Newberry	11	72.7	20.0	3.8	12.7	>18.5 Ma	Ross (1988)
Rodman	6	25.5	13.6	3.6	8.7	<e Miocene	Ross (1988)
Lava Bed	4	62.1	13.6	-12	5.6	<e Miocene	Ross (1988)
Bristol	11	29.6	19.8	-6	9.9	<e Miocene	Ross (1988)
South Cady	20	56.6	11.6	2.7	7.4	<e Miocene	Ross (1988)
Alvord	9	53.2	9.9	-6	5	<e Miocene	Ross (1988)
Southwest Cady	19	63.4	19.6	1.6	11.9	<e Miocene	Ross (in review GSAB;
Mountains	13	66.5	15.0	1.9	9.4	<~16.5 Ma	Chapter 3)
South Bristol	1	3.7	4.9	-4.5	3.8	<18.5 Ma	Wells and Hillhouse (1989)
Central Bristol	1	-0.6	7.2	-1.6	5.7	<18.5 Ma	Wells and Hillhouse (1989)
Newberry	1	-1.6	4.3	-0.7	3.4	<18.5 Ma	Wells and Hillhouse (1989)
Bullion	1	-10.1	3.7	-1.0	3.0	<18.5 Ma	Wells and Hillhouse (1989)
South Cady	1	11.6	4.2	1.1	3.4	<18.5 Ma	Wells and Hillhouse (1989)
Daggett	1	13.1	5.0	-7.8	3.8	<18.5 Ma	Wells and Hillhouse (1989)
North Cady	48	20.6	7.6	8.0	6.5	<~17 Ma	MacFadden (1990a)
<b>Sierra Nevada Mountains</b>							
Southern Sierra Nevada	4	20	24	-	-	<71 Ma	McWilliams and Li (1985)
Southern Sierra Nevada	8	45	14	-	-	<81 Ma	McWilliams and Li (1985)
Southern Sierra Nevada	10	59	16	-	-	<77 Ma	McWilliams and Li (1985)
Tehachapi	-	40	9.5	-	-	<~21 Ma <~16 Ma	Plescia and Calderone (1986)
Southern Sierra Nevada	12	-3.3	9.1	-7.7	7.6	<~16 Ma	Kanter and McWilliams (1982)
El Paso Mountains*	*	-21	6	3	6	<13.5 Ma	Burbank and Whistler (1987)
<b>North Central Mojave Desert</b>							
Jackhammer Fm.	5	54.7	8.7	12.7	6.7	<l Oligocene	Valentine and others (1993)
Lane Mt.	4	57.4	21.1	57.1	20.9	<e Miocene	Valentine and others (1993)
Pickhandle Fm.	13	-22.6	10.0	-2.0	5.9	<e Miocene	Valentine and others (1993)
Barstow Fm.	17	-1.5	7.7	7.9	5.5	<m Miocene	Valentine and others (1993)
Barstow Fm.	125	4.1	10.5	-	-	<~13 Ma	MacFadden (1990b)
Fort Irwin	6	61.2	10.8	0.4	6.7	<~21 Ma	B.P. Luyendyk (pers. com.)
Kramer Hills	19	24.4	11.5	1.0	7.3	<~20 Ma	Golombeck and Brown (1988)

N = number of sites, R,  $\Delta R$ , F,  $\Delta F$  are parameters of rotation , flattening and their 95% errors from Beck, 1980 and Demarest, 1983. < = younger than and > = older than the age listed. \* - Burbank and Whistler (1987) do not report Rotation or Flattening parameters, those listed are approximate.

### **Rosamond Hills**

An abstract by Potts and others (1989) reports that volcanic units from the Gem Hill Formation in the Rosamond Hills area of the western Mojave Desert block have a counterclockwise rotation anomaly of  $40.6^\circ \pm 24.1^\circ$  and no significant flattening anomaly. Potts and others (1989) suggest that this area has experienced  $40^\circ$  of counterclockwise rotation since the deposition of these units in early Miocene time. No data have been presented from younger units in this area which would help constrain the timing of rotation. It is possible that this enigmatic result could be the product of multiple vertical axis rotations as has been shown for other areas in the Mojave Desert block (Ross and others, 1989; Ross, in review; Chapter 3), or late Miocene local rotation due to strike-slip faulting.

### **Boron/Kramer Junction**

Golombek and Brown (1988) presented paleomagnetic results from ~20 Ma basalts in the Boron/ Kramer Junction area. Their results suggest that this area has experienced a net clockwise rotation of about  $23.8^\circ \pm 11.3^\circ$  since deposition of these basalts and they observe no significant flattening anomaly ( $2.1^\circ \pm 7.4^\circ$ ). Golombek and Brown (1988) propose that this area was rotated clockwise along with the southern Sierra Nevada some  $35^\circ$ - $45^\circ$  and then rotated counterclockwise some  $10^\circ$ - $20^\circ$  due to late Miocene strike-slip movement through the Mojave Desert block (*cf.* Garfunkel, 1974). No paleomagnetic data from overlying units in the Kramer Junction area have been published which would place a bound on the age of rotation and confirm or deny this proposed rotational history. We must view rotation in the Boron/ Kramer Junction area, then, as  $\sim 24^\circ$  clockwise and having occurred at any time after the eruption of these basalts (~20 Ma).

### **North-Central Mojave**

Some of the first paleomagnetic results to emerge from the Mojave Desert block were from the Opal Mountain-Lane Mountain area (Burke and others, 1982), who combined paleomagnetism and K-Ar dating to address problems in regional Miocene stratigraphy. They sampled volcanic units varying in age from 23 to 2 Ma and reported paleomagnetic directions for each unit. Secular variation is not averaged in their study due to the small sample size, but their data suggests both counterclockwise and clockwise deflected units (Burke and others, 1982).

Recent paleomagnetic studies of Miocene and younger volcanic deposits in the north-central Mojave Desert block appear to show mixed evidence for crustal rotation (Valentine and others, 1993). This work suggests little or no rotation for basalts from the middle Miocene age Barstow Formation, compatible with the results of MacFadden and others (1990a). Valentine and others (1993) also reported results from the Lane Mountain quartz latite, and the Pickhandle and Jackhammer Formations. Evidence for clockwise rotation lies in paleomagnetic results from the late Oligocene to early Miocene age (Burke and others, 1982) Jackhammer Formation and Lane Mountain quartz latite (Valentine and others, 1993). Paleomagnetic results from the Pickhandle Formation, which overlies the Jackhammer Formation, indicate counterclockwise deflections of magnetic directions leading Valentine and others (1993) to propose two separate, opposite sense rotations for the north central Mojave Desert block.

Valentine and others (1993) suggested that a clockwise rotation of greater than 50° in the north-central Mojave was followed by a counterclockwise rotation of about 23° (Valentine and others, 1993). The results for the Jackhammer Formation and the Lane Mountain quartz latite (Valentine and others, 1993) were plagued with a small sample size (5 sites and 4 sites, respectively) and significant flattening anomalies ( $12.7^\circ \pm 6.7^\circ$ ,

and  $57.1^\circ \pm 20.9^\circ$  respectively), making the evidence for early clockwise rotation somewhat less compelling. Paleomagnetic results from the Pickhandle Formation yield insignificant flattening anomalies ( $0.8 \pm 5.8$ ) suggesting counterclockwise rotation. Valentine and others (1993) propose that the  $\sim 50^\circ$  of clockwise rotation is coeval with rotation of the southern Sierra Nevada and the subsequent  $\sim 23^\circ$  of counterclockwise rotation is caused by shear near a transform boundary during regional early Miocene extension.

MacFadden and others (1990a) studied the magnetostratigraphy of the Barstow Formation in the Mud Hills of the central Mojave Desert block. Their sites cover a thickness of  $\sim 1$  km of fluvial and lacustrine sediments deposited between  $\sim 19.3$  Ma to 13.4 Ma (MacFadden and others, 1990a; Woodburne and others, 1990). Their paleomagnetic data pass both fold and reversal tests and show an insignificant amount of rotation ( $4.1^\circ \pm 10.5^\circ$ ; MacFadden and others, 1990a). Due to a lack of correlation of rotation to stratigraphic position, MacFadden and others (1990a) conclude that negligible rotation has taken place since initiation of deposition of the Barstow Formation. However, because there appears to be a significant unconformity near the base of the magnetostratigraphic section, a more conservative alternative conclusion from their data is that little or no vertical axis rotation has occurred in the Mud Hills since  $\sim 17.6$  Ma (the base of the last magnetic chron correlated by MacFadden and others, 1990a) instead of the initiation of Barstow sedimentation at  $\sim 19.3$  Ma.

### **Northern Cady Mountains**

The magnetostratigraphy of the Hector Formation in the northern Cady Mountains has recently been studied by MacFadden and others (1990b). Their results for 48 sites over  $\sim 360$  m of strata pass a reversal test and suggest  $20.6^\circ \pm 7.6^\circ$  of clockwise rotation (MacFadden and others, 1990b). The authors notice a slight, yet significant flattening

anomaly of  $8.0^\circ \pm 6.5^\circ$ , but do not attempt to explain this observation (MacFadden and others, 1990b). This flattening anomaly could be due to many possible reasons and raises a slight concern over the significance of their conclusions. MacFadden and others (1990b) correlate their magnetostratigraphy to the magnetic polarity time scale constrained by K-Ar dates and biostratigraphic control (Miller, 1980) which suggest that the section represents deposition between ~23 Ma and ~16 Ma. The authors find no trends of rotation in their data and conclude that the northern Cady Mountains was rotated clockwise sometime younger than ~16 Ma.

### **Central Mojave**

Ross and others (1989) reported paleomagnetic results from early Miocene volcanic units of 7 structurally distinct areas in the central Mojave Desert block: Newberry Mountains, Rodman Mountains, Lava Bed Mountains, Bristol Mountains, southern Cady Mountains, southwestern Cady Mountains, and Alvord Mountains. All of these structural blocks except the Alvord Mountains (discussed below) reside in the upper plate of the Daggett extensional terrane (Dokka, 1986, 1989; Ross and others, 1989). The volcanic flows represent pre- and syn-extensional deposits which experienced tilting and crustal extension during early Miocene time. This regional study grouped 4 to 20 sites to obtain mean directions for each structural block, with each block showing a clockwise rotation anomaly and most showing no significant flattening anomaly (Ross and others, 1989; see Table 4.1).

The mean directions from every structural block show a decrease in dispersion after application of a structural correction (with the exception of the Lava Bed Mountains, where all sites collected had the same structural attitude) and movement of the mean inclination toward the reference inclination suggesting acquisition of the characteristic direction prior to tilting (Ross, 1988). Also, the Newberry Mountains,

Bristol Mountains, and southern Cady Mountains blocks contain both reversed and normal polarity sites, though the paucity of normal polarity sites renders reversal tests untenable. The wide geographic extent, consistency of these magnetic directions and the apparent correspondence in timing and location of clockwise rotation and extensional activity, led Ross and others (1989) to suggest that this coherent rotation was caused by vertical axis rotation of upper plate fault blocks during regional early Miocene extension.

**Southwest Cady Mountains.** The southwest Cady Mountains is a structural block studied by Ross and others (1989) which showed a  $>120^\circ$  clockwise rotation anomaly. The rotation of this block was hypothesized to have been caused by two separate tectonic events:  $\sim 50^\circ$  of early Miocene rotation, and  $\sim 70^\circ$  due to recent movements on bounding faults. Ross (in review) presents new paleomagnetic data which suggest that overlying strata have rotated  $67^\circ \pm 15^\circ$  clockwise since  $\sim 14$  Ma supporting a two-stage rotation history for the southwestern Cady Mountains. When this younger rotation is removed, the early Miocene basalts retain  $63^\circ \pm 20^\circ$  of clockwise rotation which is consistent with paleomagnetic data from the rest of the Daggett terrane (Ross, in review).

The lower Miocene basalts sampled in the southwest Cady Mountains unconformably overlie older, extended volcanic strata (Ross, in review). Paleomagnetic results from these basalts show consistent, well-defined directions which pass a fold test and yield statistically the same direction as the older extended strata (Ross, in review). Though only reversed field samples are observed, a path of secular variation is observed through an approximately 100 m thick section of stacked flows sampled with six sites suggesting at least some averaging of secular variation (Ross, in review). The mean directions from the southwest Cady Mountains all show significant clockwise rotation anomalies, but no significant flattening anomalies. The observation of two sequential rotations, matched with critical structural relationships, led Ross (in review) to conclude



that the regional clockwise rotation of the central Mojave Desert block occurred after local extension in the southwest Cady Mountains and prior to ~16 Ma.

**Alvord Mountains.** Paleomagnetic results from the Alvord Mountains are presented by Ross and others (1989). Their study sampled early Miocene flows from the Spanish Canyon Formation and the Alvord basalts. These basalts have a  $53^\circ \pm 9.9^\circ$  clockwise rotation anomaly and a slight flattening anomaly ( $-6^\circ \pm 5^\circ$ ). A reversal test is not possible for data from the Alvord Mountains, but they show a significant decrease in dispersion upon tectonic correction which suggests that the magnetic directions were acquired prior to tilting (Ross, 1988). Ross and others (1989) suggested that since this area is located north of the northern Cady Mountains area which experienced rotation younger than 16 Ma (MacFadden and others, 1990b), and the Alvord Mountains did not experience early Miocene extension along with the Daggett terrane, that the Alvord Mountains probably rotated clockwise younger than ~16 Ma. Currently, no data from overlying units have been published to place a boundary on the time of rotation.

### **Northeastern Mojave**

Recent studies in the Fort Irwin and Goldstone areas show intriguing results. Magnetic directions from a thick stack of flat lying basalt flows from the Goldstone Deep Space Network show no significant difference in declination from the present axial dipole field direction (D. MacConnell, personal communication, 1992). These undated basalts are all one polarity and do not average secular variation of the earth's magnetic field (D. MacConnell, personal communication, 1992). Paleomagnetic results from basalt flows in the Fort Irwin Military Reserve suggest that clockwise rotation may have occurred there (B. P. Luyendyk, personal communication, 1993). Results from one locality suggest that about  $60^\circ$  of clockwise rotation has occurred younger than ~21 Ma (B. P. Luyendyk, personal communication, 1993). Other data suggest that clockwise

rotation or no rotation of early Miocene(?) basalts may have occurred (B. P. Luyendyk, personal communication, 1993). None of these studies are published to date and ongoing work is being carried out to better quantify and qualify these possible rotations.

### **Peach Springs Tuff**

Recent studies have been carried out by Wells and Hillhouse (1989) studying the paleomagnetism of the Peach Springs tuff. The ~18.5 Ma Peach Springs tuff (Young and Brennan, 1974; Neilson and others, 1990) is a large volume ash flow tuff that has been proposed to extend from near its vent on the Colorado Plateau to near Barstow in the central Mojave Desert block (Glazner and others, 1986). Wells and Hillhouse (1989) present paleomagnetic results for many of these outcrops through the Colorado River extensional corridor, the eastern Mojave Desert block, and into the right-lateral strike-slip tectonic regime in the central Mojave Desert block. Paleomagnetic results from proposed Peach Springs tuff in the southeastern Newberry Mountains show no significant rotation with respect to the paleomagnetic direction from the stable Colorado Plateau, suggesting that the Newberry Mountains has not rotated since ~18.5 Ma (Wells and Hillhouse, 1989). Data from similarly correlated outcrops suggest that the Bristol Mountains have not rotated, while the southern Cady Mountains have rotated slightly (~12°) clockwise and the Daggett Ridge area near Barstow has rotated slightly clockwise (~13°). These data are very important because they provide critical constraints for the timing of rotation in the eastern and central Mojave Desert block.

A critical assumption inherent in the study by Wells and Hillhouse (1989) is that every outcrop that they have sampled is, in fact, the Peach Springs tuff. The observed magnetic direction for each site has been compared to the magnetic direction of the Peach Springs Tuff on the stable Colorado Plateau (Wells and Hillhouse, 1989). The Peach Springs Tuff is a quickly deposited rhyolitic ignimbrite which cooled during an

excursion of the earth's magnetic field (Young and Brennan, 1974; Wells and Hillhouse, 1989). The magnetic direction from the Peach Springs tuff on the Colorado Plateau is deflected 33° clockwise and is has an inclination ~20° shallower than the present axial dipole field direction (Young and Brennan, 1974; Wells and Hillhouse, 1989). The magnetic declination for an outcrop of the Peach Springs tuff that had not rotated since emplacement, would be approximately the same declination as a lower Miocene tuff that was deposited while the earth's magnetic field was in an axial dipolar position and subsequently has rotated clockwise ~40°. In some areas of the Mojave Desert block where there is evidence for clockwise rotation, it is impossible to tell the two cases described above apart, unless one knows *a priori* that the tuff sampled was or was not the Peach Springs tuff. Using the Peach Springs tuff as an instantaneous time/tectonic marker is extremely powerful, but one must be certain that each individual outcrop is, in fact, the Peach Springs tuff.

### **Separation of Paleomagnetic Data by Timing**

The paleomagnetic data discussed above is presented in Figure 4.2. Reported rotation values for rocks older than ~16 Ma are shown for areas which display deflected paleomagnetic directions. Areas in which the age of the rotation is poorly known (i.e., no paleomagnetic data for younger strata) are designated by a question mark on the arrow. In Figure 4.3 one can see that all but two areas are suspected of Pre-16 Ma clockwise rotation. One of the anomalous counterclockwise deflected areas (c - Rosamond Hills) has no data for overlying or nearby younger units rendering the timing and cause of the rotation suspect. The other area of anomalous counterclockwise rotation (e-Pickhandle Formation) is not understood.

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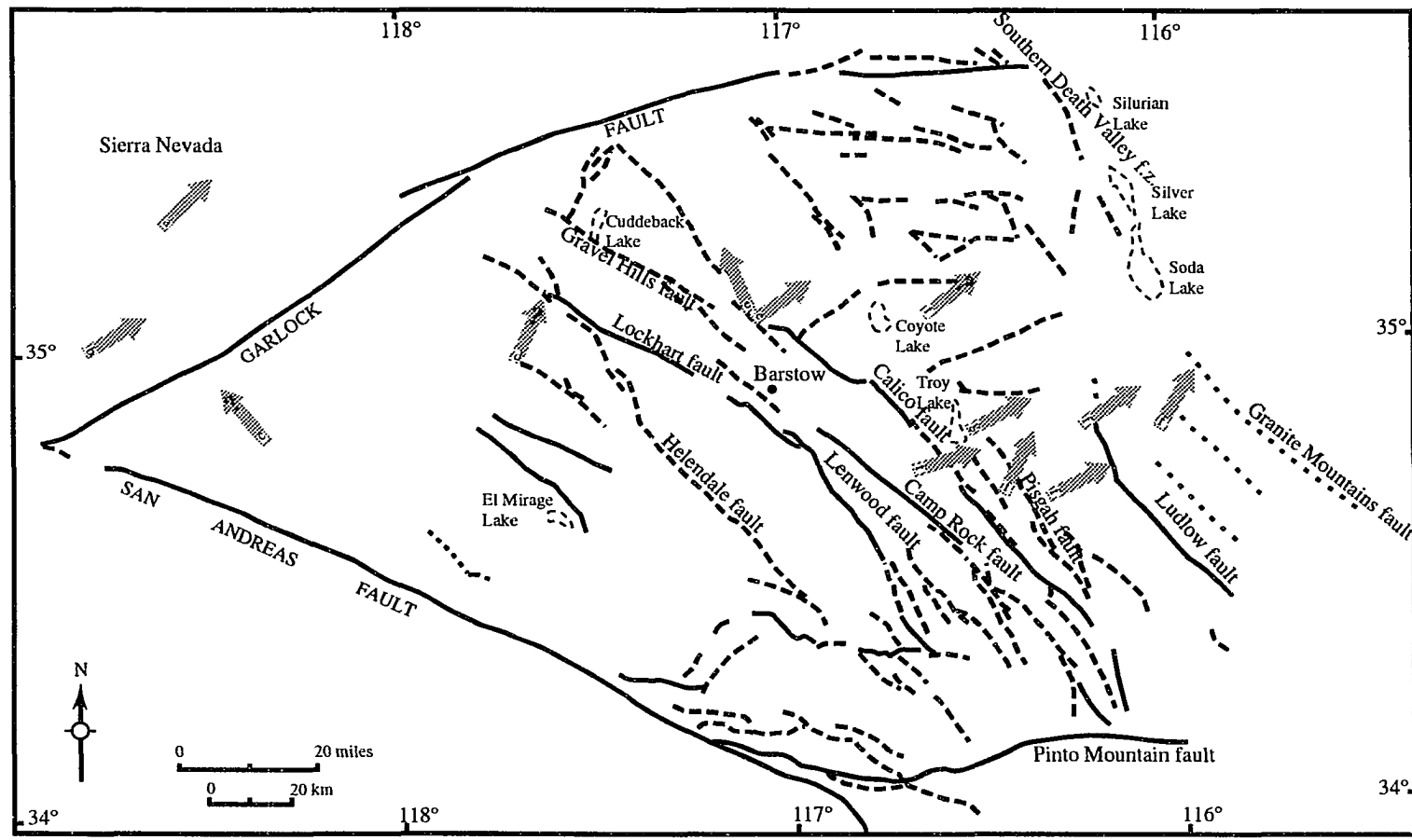


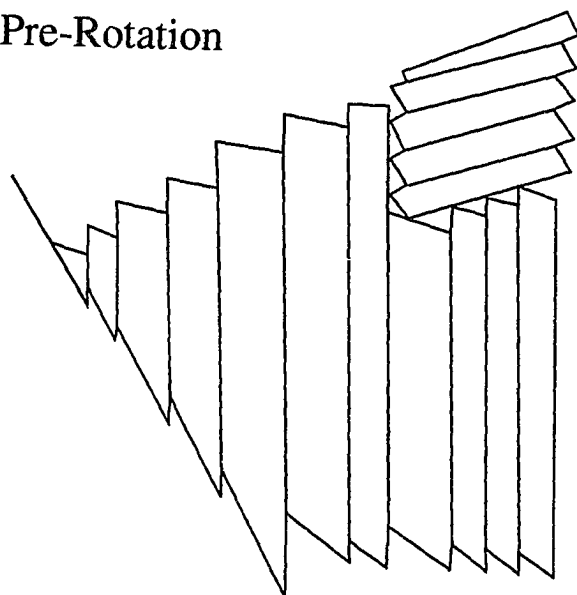
Figure 4.3 Pre-16 Ma rotations in the Mojave Desert. References to paleomagnetic studies: a= Kanter and McWilliams (1982), b= McWilliams and Li (1985), c= Potts and others (1989), d= Golombeck and Brown (1988), e= Valentine and others (1993), f= Ross and others (1989), and g= Ross (in review, Chapter 3). ?= time of rotation uncertain.

### **Models for Late Miocene and Younger Rotation**

Garfunkel (1974) proposed a geometric model to explain the present configuration of right-lateral strike-slip faults in the Mojave Desert block (Figure 4.4). Garfunkel's model suggested that movement of these right-lateral faults caused the intervening crustal panels to rotate counter-clockwise and suggested that paleomagnetism could be used to test his model. Subsequent work has shown that the initiation of movement on these faults occurred younger than ~13 Ma (Dokka and Travis, 1990ab) indicating that the rotation proposed by Garfunkel (1974) must be late Miocene or younger. Carter and others (1987) incorporated these counter-clockwise rotations into their geometric model which predicts clockwise rotations of the same age in areas bounded by northwest-trending right-lateral faults and northeast-striking left-lateral faults (Figure 4.5). A look at Figure 4.2 shows that the well-determined Mud Hills paleomagnetic results (MacFadden and others, 1990) indicate no net rotation since ~13 Ma, and that the Peach Springs tuff result in the Newberry Mountains (Wells and Hillhouse, 1990) yields no net rotation since ~18.5 Ma. Both the Mud Hills and the Newberry Mountains lie in structural blocks proposed to have rotated counter-clockwise by Garfunkel (1974) and Carter and others (1987). Because these areas do not show counterclockwise deflected paleomagnetic directions, these proposed counter-clockwise rotations probably do not exist.

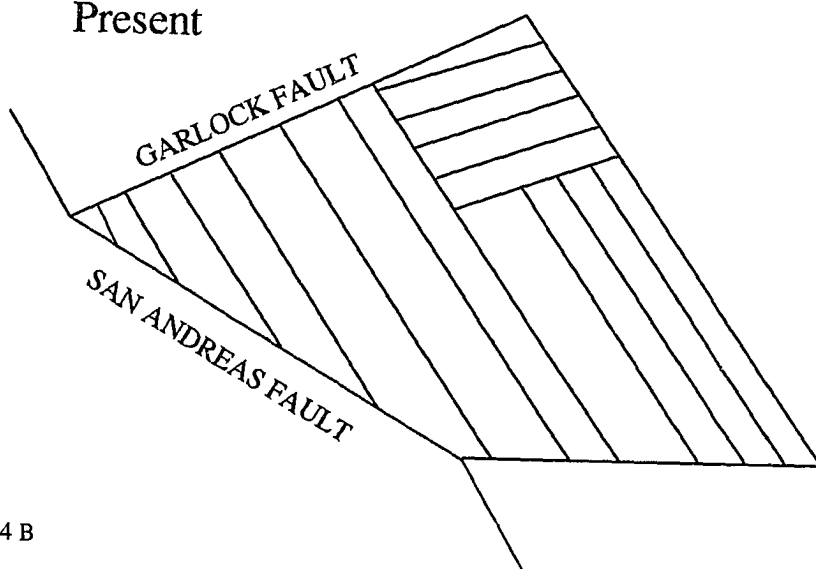
Luyendyk and others (1980, 1985) and Carter and others (1987) proposed clockwise rotations due to the interactions of antithetic strike-slip faults in the Mojave Desert block. Two studies have suggested late Miocene and younger clockwise rotations - the northern Cady Mountains and the southwest Cady Mountains (Figure 4.2). The northern Cady Mountains have been rotated ~21° clockwise (MacFadden and others, 1990) and lie in the area predicted by Carter and others (1987) to have

Pre-Rotation



4.4 A

Present



4.4 B

Figure 4.4. Slip and rotation model of Garfunkel (1974). A depicts a pre-slip and rotation configuration. Coincident with right lateral slip on NW-striking faults and left lateral slip on NE-striking faults the crustal blocks rotate to their present configuration (B). Modified from Garfunkel 1974).

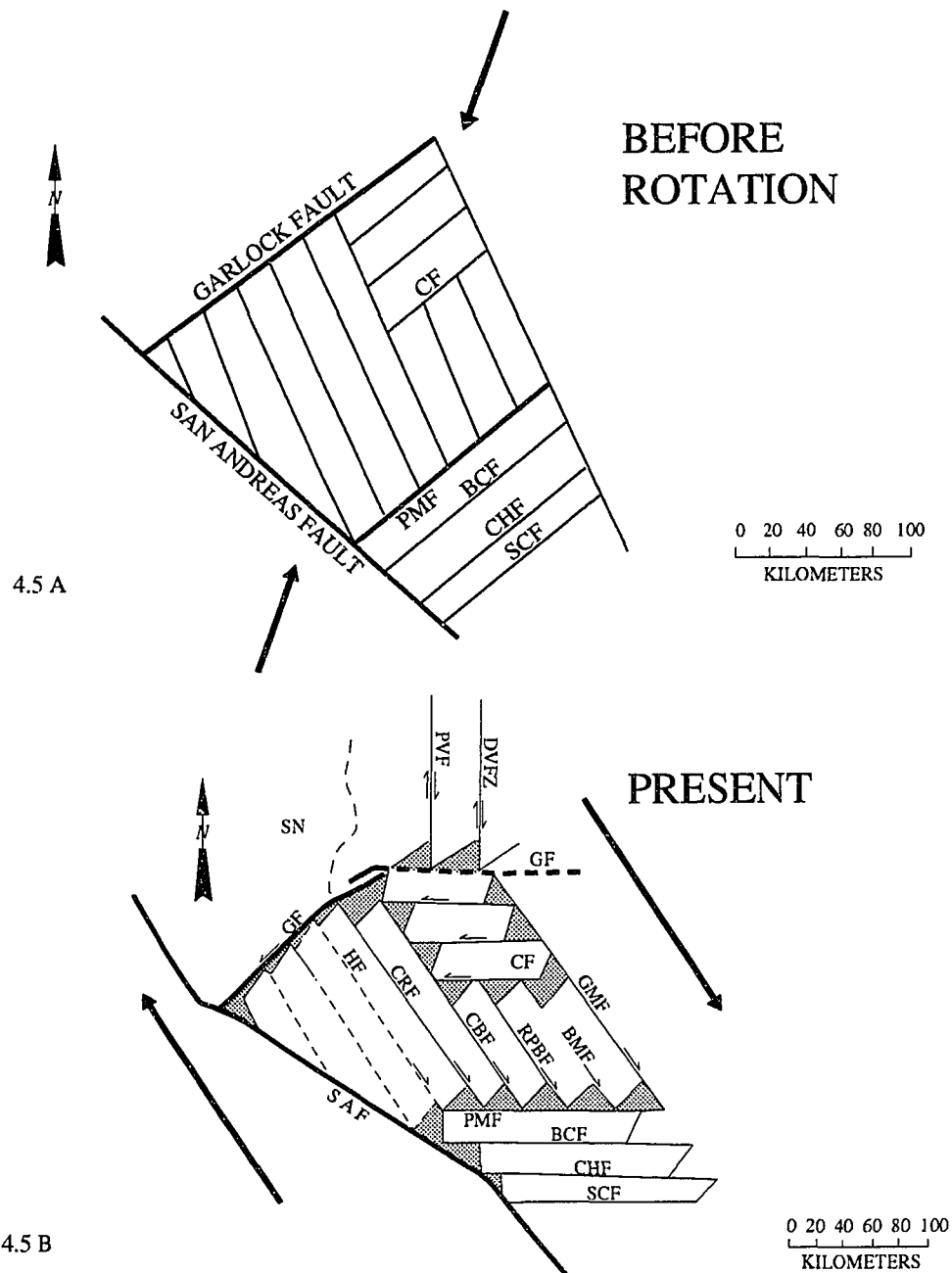


Figure 4.5 Rotational model of Carter and others (1987). A represents late Miocene pre-rotational configuration with NE-SW maximum compressional stress. B shows response to NW directed dextral shear. Abbreviations are: CF = Cady fault, PMF = Pinto Mountain fault, BCF = Blue Cut fault, CHF = Chiriaco fault, SCF = Salton Creek fault, GF = Garlock fault, SAF = San Andreas fault, PVF = Panamint Valley fault, DVFZ = Death Valley fault zone, HF = Helendale fault, CRF = Camp Rock fault, CBF = Calico/Blackwater fault system, RPB = Rodman/Pisgah/Bullion fault system, BMF = Bristol Mountains fault, and GMF = Granite Mountain fault. Modified after Carter and others (1987).



rotated  $\sim 40^\circ$  clockwise. The southwest Cady Mountains have been rotated  $\sim 67^\circ$  clockwise since  $\sim 14$  Ma (Ross, in review) and lie just outside the area predicted to have rotated clockwise  $\sim 40^\circ$  by Carter and others (1987). Carter and others (1987) generally predicted clockwise rotations correctly, but the observed amounts appear more complicated than their model predicts. Dokka and Travis (1990a) incorporate much of this paleomagnetic information into their model for late Miocene to present deformation of the Mojave Desert block.

### **Pre- $\sim 18$ Ma Rotations**

Ross and others (1989) suggested that early Miocene clockwise rotations in the central Mojave Desert block were caused by regional extension. Other models have subsequently been proposed which associate rotations with extensional activity (Bartley and Glazner, 1991; Valentine and others, 1993). A recent study by Ross (in review) of the southwest Cady Mountains concludes that clockwise rotation occurred after local extension and that the consistency of kinematic indicators suggests that the entire extensional belt has been rotated coherently. This study concludes that regional clockwise rotation was not related to extension.

The paleomagnetic studies which suggest clockwise rotation and have good age control are in the southern Sierra Nevada and the southwest Cady Mountains (Figure 4.3). The southern Sierra Nevada is in the shape of a large orocline. Paleomagnetic data show a progressive increase in clockwise deflection to the south (up to  $\sim 60^\circ$ ) which matches structural and isotopic deflections (Kanter and McWilliams, 1982; McWilliams and Li, 1985). This oroclinal rotation was complete by  $\sim 16$  Ma and occurred at least partially after  $\sim 23$  Ma (Plescia and Calderone, 1986). The southwest Cady Mountains also contain data suggesting a pre  $\sim 16$  Ma clockwise rotation of  $\sim 63^\circ$  clockwise (Ross, in review). This matches with the data for the surrounding mountain ranges which

suggest an average of  $\sim 50^\circ$  clockwise rotation prior to  $\sim 18.5$  Ma. Other paleomagnetic data throughout the Mojave Desert block also suggest clockwise rotation, but have less well-determined age controls. Because the majority of early Miocene rocks in the Mojave Desert display clockwise declination anomalies, we suggest that a major rotation occurred after regional extension and prior to  $\sim 18.5$  Ma. A simple mean of rotation values for the areas which suggest early Miocene clockwise rotation yields  $51.1^\circ \pm 15.6^\circ$  ( $1\sigma$ ), probably not a valid method of producing an average rotation for the region, but provides a first approximation.

## **PRE-MIOCENE STRUCTURAL TRENDS**

### **Mesozoic Thrust Trends**

Paleozoic and Mesozoic sedimentary and volcanic rocks (and their metamorphosed equivalents) crop out from place to place throughout the central and western Mojave Desert block (Burchfiel and Davis, 1980). It has long been noticed that Paleozoic strata with cratonal to miogeoclinal affinities are abutted against rocks of the same age with an eugeoclinal affinity (Burchfiel and Davis, 1980). Thrusts which carry eugeoclinal rocks over Miogeoclinal to cratonal rocks in the northern and central Mojave Desert block have been named the eastern California thrust system (ECTS; Walker, 1988; Walker and others, 1990ab). The presumed traces of these thrusts trend roughly north-south toward the central Mojave, where they turn clockwise and head westerly (Walker and others, 1990ab).

Recently J. K. Snow (1992) reconstructed Permian thrusts in the Death Valley area and suggested correlations for related thrusting southward in the Mojave Desert block. Snow (1992) produced a reconstruction which suggests that prior to Tertiary extension, this thrust system formed a continuous belt hundreds of kilometers in length. Because this belt of thrusting continues for hundreds of kilometers to the north, we

suggest that this clockwise bend in the thrust belt in the same area as inferred clockwise rotation is more than a coincidental occurrence. Glazner and others (1989) suggested that bends in the ECTS could be reconstructed by removing the effects of early Miocene extension in this area. Walker and others (1990a) attempted this reconstruction, but failed to remove the bend in the thrust belt completely. Current understanding of the Miocene extension in the Mojave Desert block does not permit this type of detailed reconstruction, as has been accomplished in the Basin and Range province (e.g., Wernicke and others, 1988 ; Snow and Wernicke, 1989). This clockwise bend of Mesozoic and older thrusts in the central Mojave Desert block may have been caused by the same event which produced clockwise rotation elsewhere in the Mojave Desert block.

### **Jurassic Independence Dike Swarm**

The Independence dike swarm is a NW-striking set of late Jurassic (~148 Ma; Chen and Moore, 1979) hypabyssal dioritic to granitic dikes which were described and studied by and Moore and Hopson (1961). The offset of this swarm proposed by Smith (1962) remains the dominant argument for large left-lateral displacement on the Garlock fault which forms the northern boundary the Mojave Desert block. James (1989) proposed that dikes of similar age and strike as the Independence dike swarm can be found in the central Mojave Desert block and continue southeastward into the eastern Transverse Ranges without showing deviation from strike. James (1989) and Bartley and Glazner (1991) have used this correlation as evidence against regional crustal rotation in the central Mojave Desert block. Their argument assumes that the "Independence dike swarm" was emplaced parallel over a very large region, though there is no *a priori* reason that this is required.

The complex late Mesozoic tectonic history of the Mojave Desert block argues strongly against the maintenance of simple geometric relationships between ~100 Ma and 20 Ma. Recent petrologic and thermochronologic work by Henry and Dokka (1992) demonstrated that the central and western Mojave Desert block was the site of early Cretaceous? (pre-92 Ma) tectonic thickening and associated granulite metamorphism, followed by major lithospheric thinning and extension. Because there is no paleomagnetic data from either the dikes or the surrounding rocks, the hypothesis of non-rotated dikes in the central Mojave Desert block is untested. If the correlation of Independence dikes (James, 1989) is valid and the hypothesis of no rotation is true, then these dikes may be used as a boundary for the effects of early Miocene rotation in the central Mojave Desert block.

## **THE ORIGIN OF EARLY MIOCENE ROTATION**

In order to address the origin and mechanism which produced the early Miocene regional rotation, we must first remove all subsequent deformation and observe the pattern of data suggesting rotation in their original configuration. This procedure involves both assumptions and interpretations of younger structures in the Mojave Desert. The regional clockwise rotation discussed in this paper must have occurred prior to ~18.5 Ma, therefore, we must remove any deformation younger than ~18 Ma in order to obtain a reconstruction for the Mojave Desert and the southern Sierra Nevada immediately after regional rotation. The present structure of the Mojave Desert block is dominated by recent to active strike-slip faults that are younger than ~13 Ma (Dokka, 1983; Dokka and Travis 1990a). The movement and local rotations attributed to these strike-slip faults must be removed before we may determine an appropriate model to explain this phenomenon of regional clockwise rotation.

### **Removal of Post-18 Ma Deformation**

Some basic assumptions related to reconstruction of the Mojave Desert block are:

- 1) The Last Chance thrust system (LCTS) and the eastern California thrust system (ECTS) are found in the Mojave Desert block as proposed by Snow (1992) and Walker and others (1988), respectively.
- 2) The Independence dike swarm occurs in the Mojave Desert block as proposed by James (1989).
- 3) Paleomagnetic data suggesting clockwise rotations in the Mojave Desert block and Sierra Nevada are robust.

The above pre-Miocene structural features and paleomagnetic data, along with the boundaries of early Miocene regional extension of Dokka (1989), are followed through steps in this reconstruction (Figures 4.6, 4.7, 4.8, 4.9).

Figure (4.6) depicts the present configuration of the Mojave Desert block. Note that the LCTS (Snow, 1992), the ECTS (Walker and others, 1988), the proposed Independence dikes (James, 1989), the boundaries of early Miocene extension (Dokka, 1989) and areas of possible clockwise rotation are shown (open arrows). The first step to determining the origin of the regional rotation is to remove subsequent deformation. The model of Dokka and Travis (1990) has been chosen to remove the late Miocene and younger deformation in the Mojave Desert. Their model is the most contemporary reconstruction, reflecting the current state of tectonic information, and mainly involves removing accumulated right-lateral slip from northwest-striking faults in the eastern Mojave Desert block. Other orientations of faults are reconstructed using kinematic and geometric controls, and late Miocene and younger tectonic rotations interpreted from paleomagnetism are removed (Dokka And Travis, 1990). The left-lateral offset along

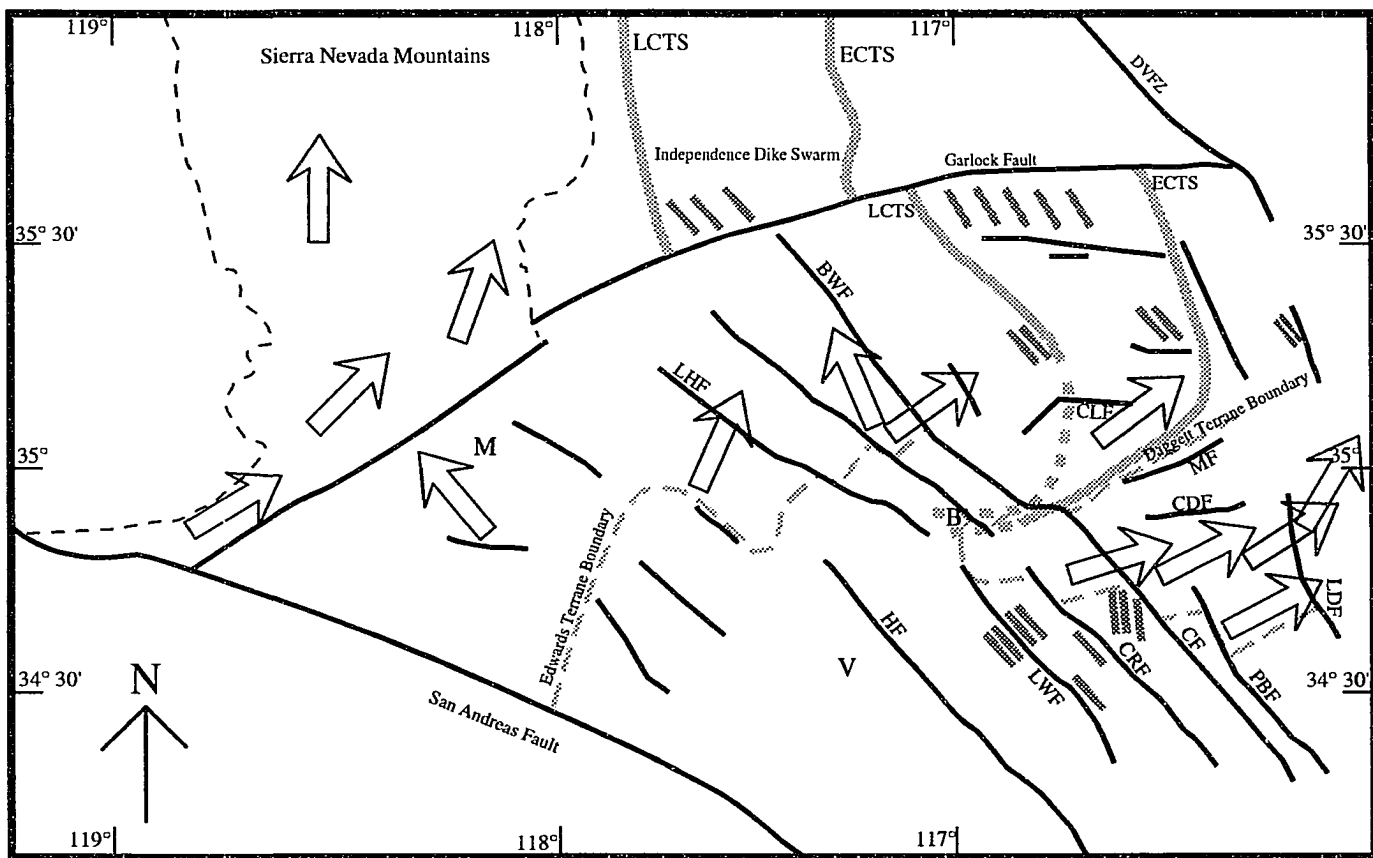


Figure 4.6 Mojave Desert at present. LHF=Lockhart fault, HF=Helendale fault, CRF=Camp Rock fault, BWF= Blackwater fault, CF=Calico fault, PBF=Pisgah/Bullion fault, LDF=Ludlow fault, CDF=Cady fault, MF=Manix fault, CLF=Coyote Lake fault, DVFZ=Death Valley fault zone. Rotations inferred from paleomagnetic studies (arrows), boundaries of early Miocene extension for the Daggett and Edwards terranes, and proposed pre-Miocene tectonic features (LCTS=Last Chance thrust system [after Snow, 1992], ECTS=eastern California thrust system [after Walker and others, 1990ab] and the Independence dike swarm [after James, 1989]).

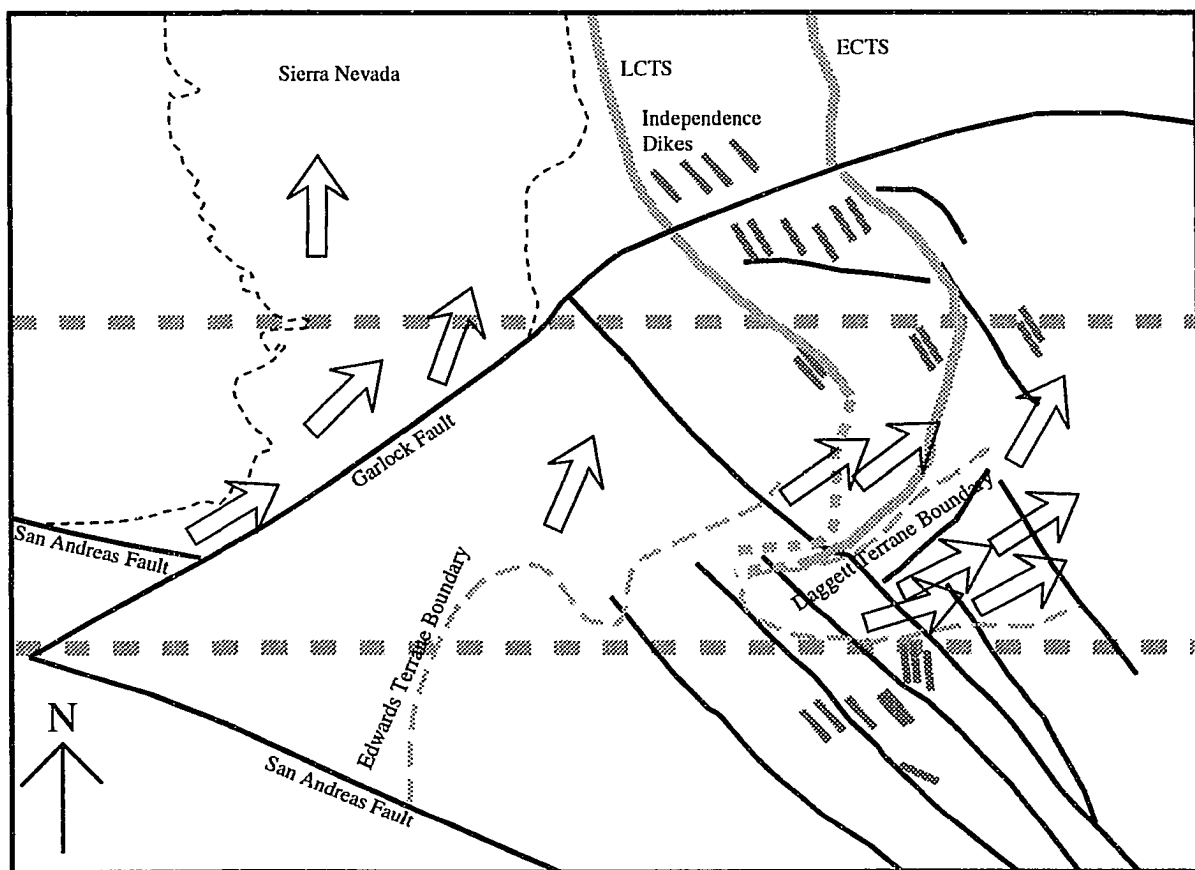


Figure 4.7 Reconstructed Mojave Desert at ~18 Ma. Reconstructed by removal of post mid-Miocene dextral deformation and sinistral deformation on the Garlock fault. Offset of the San Andreas fault is an artifact of the reconstruction. Arrows designate rotations interpreted from paleomagnetic studies. Shaded thick, dashed lines designate apparent boundaries of rotation and where inflections in the Sierra Nevada, Last Chance thrust system and eastern California thrust system.

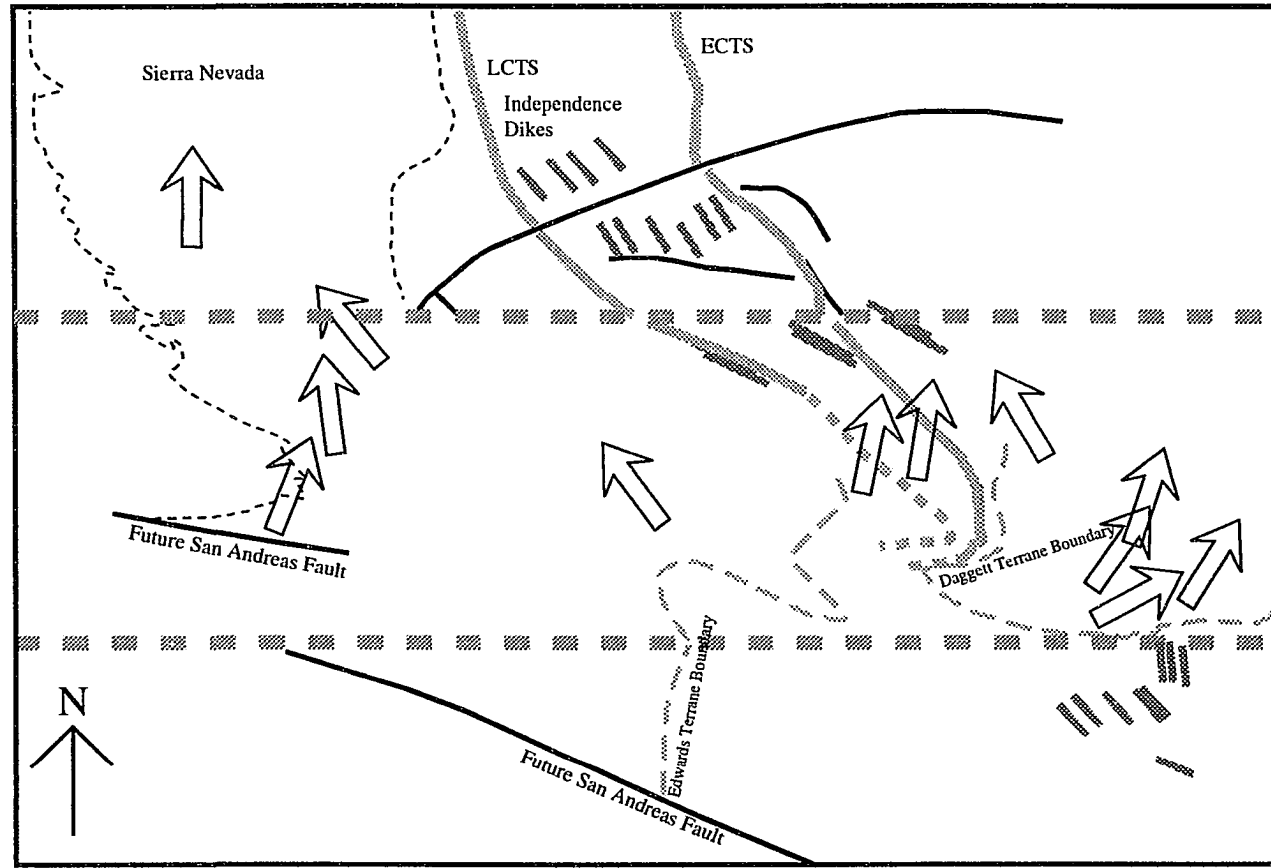


Figure 4.8 Reconstructed Mojave Desert at ~ 20 Ma by evenly distributed shear. An E-W simple shear of 50° has been removed. This results in approximate alignment of Independence Dikes, Last Chance thrust system, eastern California thrust system and the western edge of the Sierra Nevada. Rotations interpreted by paleomagnetism are also approximately removed.



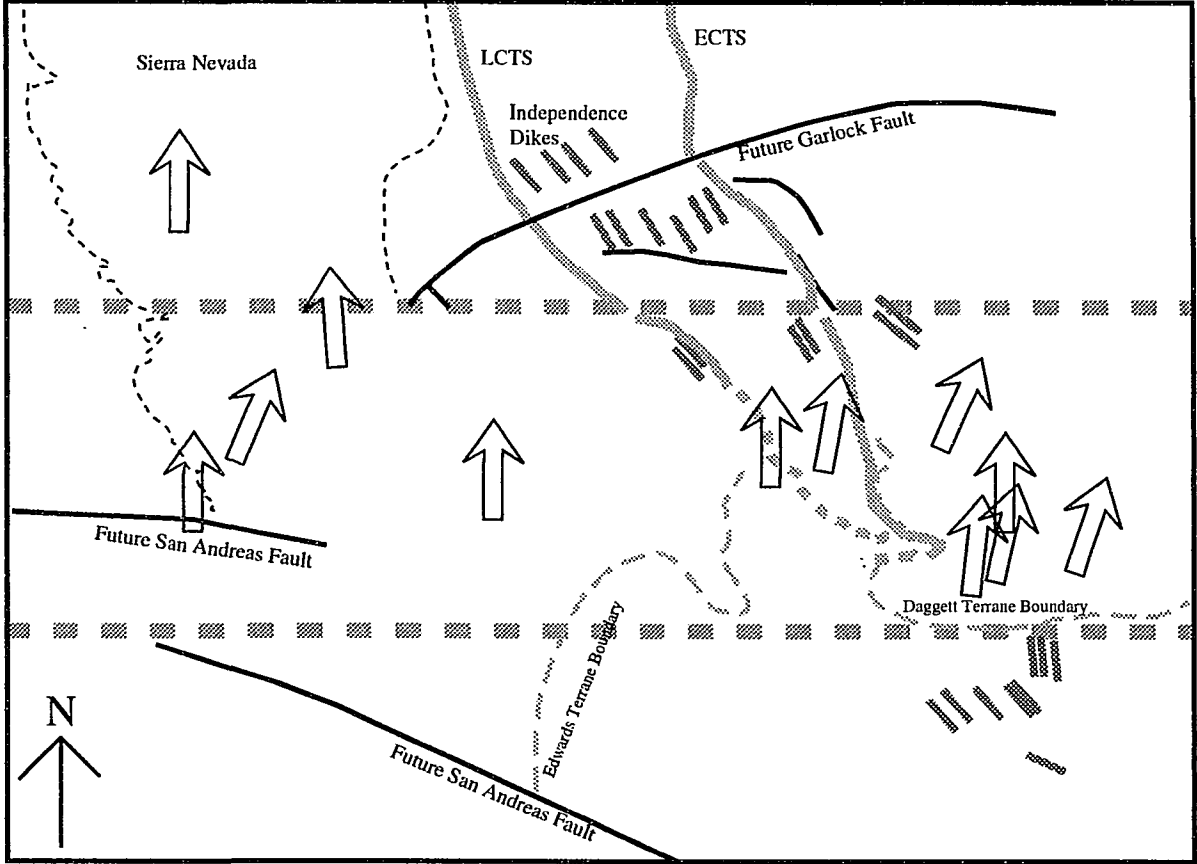


Figure 4.9 Reconstructed Mojave Desert at ~20 Ma by southward progressive shear. Bends in traces of thrust systems and southern Sierra Nevada, rotations and offset of Independence dike swarm removed using progressive shear to the south.

the Garlock fault is also removed during this step following Burbank and Whistler (1987), who interpreted a late Miocene to recent age of this structure.

With the late Miocene and younger deformation removed (Figure 4.7), we may now get a feeling for the original pattern of deformation. The basic pattern of clockwise rotation appears to be confined to an E-W corridor (Figure 4.7). The LCTS, ECTS and Independence dikes are now juxtaposed from their counterparts across the Garlock fault. Notice that the traces of these thrust systems are deflected toward the west, similar to the bend in the western trace of the Sierra Nevada Mountains at its southern end. The southeastward trend of the Independence dike swarm is broken at about the same latitude as the bends in the thrust traces, and appears again to the southwest. All of the areas containing clockwise deflected paleomagnetic directions lie between the inflections in the thrust systems to the north and the proposed Independence dike swarm to the south, and the bends in the LCTS and the ECTS reconstruct close to the same latitude as the bend in the southern Sierra Nevada, within the E-W zone which experienced clockwise rotation (Figure 4.7). The northern inflection in the thrust systems and the Sierra Nevada align forming the northern boundary of this E-W zone, and the first appearance of Independence dikes to the south marks the southern boundary (Figure 4.7). The width of this zone is ~80 km.

The southern Sierra Nevada, the ECTS and the LCTS all display a deflection to the right as they enter the E-W zone of deformation. The Independence dikes show an offset to the right across this zone (note, however, that they do not crop out in the highly rotated area). The geometries of 1) the bend in the southern Sierra Nevada, 2) the bends in the thrust systems and, 3) the offset of the Independence dike swarm all suggest a right-lateral shear system oriented approximately E-W ( $\pm 10^\circ$ ). This reconstruction is interpreted to demonstrate that regional rotation occurred in an ~E-W oriented zone of right-lateral deformation.

### **A Model for Early Miocene Clockwise Rotation**

The zone of deformation suggested by reconstruction of the Mojave Desert to ~18 Ma can be interpreted in different ways. This zone of deformation can be approximated using an evenly distributed penetrative strain producing ~50° of clockwise rotation as suggested by paleomagnetic data (Figure 4.8). This simple reconstruction of the Mojave Desert straightens the western edge of the Sierra Nevada fairly well, takes most of the bends out of the LCTS and the ECTS and realigns the proposed Independence dike swarm (Figure 4.8). Boundaries of early Miocene extension move closer to a N-S orientation as suggested by Dokka (1989) and Ross (Chapter 3; in review). This reconstruction leaves bends in the southern ends of the Sierra Nevada, ECTS and LCTS, and rotates some proposed Independence dikes in the northeastern portion of the Mojave Desert out of parallelism with the regional trend of the swarm. A possible explanation is that the northern boundary is misplaced (too far north) or the boundary may not be linear. The evenly distributed strain leaves some areas rotated and over-corrects for other areas, particularly leaving the more southerly areas under-corrected.

Because the southern portion of the Sierra Nevada is bent progressively (oroclinally) southward, and paleomagnetic data there imply increasing clockwise rotation to the south, an alternative reconstruction is to remove a southwardly progressive strain. This alternative is presented in Figure 4.9. Like the uniformly distributed strain hypothesis, this approach does not create a perfect reconstruction. This reconstruction was achieved by moving the western edge of the Sierra Nevada eastward until the edge formed a continuous linear boundary. Features within the deformation zone were moved eastward equivalent to the amount of the portion of the western edge of the Sierra Nevada immediately east of the feature. The traces of the LCTS and ECTS are straightened fairly well, but not as well as the reconstruction in

figure 4.8. The rotations appear to be corrected reasonably well, but the southern ends of the thrust traces are not straightened completely.

The reconstruction shown in figure 4.8 assumes that an evenly distributed right-lateral shear occurred over an ~80 km wide zone facilitating regional clockwise rotation within this zone. This reconstruction predicts ~90 km of offset on this zone and tends to over-correct for rotations at the northern edge, while under-correcting rotations at the southern edge. The reconstruction presented in figure 4.9 assumes that the rotation is caused by an orocline and that the rotation increases toward the southern boundary which is required to be a fault, as discussed below. This reconstruction predicts about 60 km of right-lateral offset across this zone and appears to remove rotations fairly well. Because the western edge of the southern Sierra Nevada bends smoothly and the paleomagnetic data there also indicate a southward increasing rotation, I think that figure 4.9 is probably the most adequate reconstruction at this time.

At least two general tectonic models may explain the zone of deformation and the resultant rotations. The first model (Model 1) considers that an ~E-W dextral fault approximately coincident with the southern boundary of the deformation zone was active in early Miocene time. The rotated structures would be manifestations of drag along this fault. This model implies there should be a major early Miocene age strike-slip fault exposed in the central to southern Mojave Desert. Such a fault has not yet been identified. The second and preferred model (Model 2), proposes that an oroclinal flexure (signified by the Sierra Nevada orocline) was produced by distributed shear along the E-W zone of deformation. In contrast to Model 1, a major bounding structure at the southern edge of the deformation zone is not required for this model. Model 2 predicts, however, that an oroclinal bend should be apparent as one moves northward into this zone, which is also currently not recognized. Both models could accommodate a southward-increasing bend, but Model 1 implies a discrete fault along which some

motion has occurred, while the Model 2 does not. If one projects the western edge of the proposed Independence dike swarm to the southern edge of the zone of deformation from the north and the south, the E-W right-lateral offset is ~80 km, very close to the predictions of the reconstructions (60 km-90 km) without requiring additional movement on a fault. The preferred interpretation is that of an oroclinal bend, for no major E-W fault has been proposed in the Mojave Desert, no additional dextral motion is required to re-align the Independence dike swarm.

Although the reconstructions are simple and appear to explain many of the pertinent observations for the evolution of the Mojave Desert, it is prudent to discuss possible problems areas:

- 1) The pre-Tertiary markers utilized to constrain the reconstruction are not certain. Assumptions regarding the LCTS, ECTS and Independence dike swarm are difficult to assess because these features are incompletely known and may have been disrupted by several tectonic events. The reconstruction does, however, provide an explanation for the suggested patterns of these features without resorting to additional deformations. Obviously, more investigation is required to address the assumptions of simple linear traces of the thrust systems and for the existence and pattern of the Independence dike swarm in the Mojave Desert.

- 2) The exact areal extent of the zone of deformation is poorly known. This reconstruction is limited to the extent of the Mojave Desert block and the southern Sierra Nevada because of the complicated Neogene tectonic histories (regional extension and/or translation) of rocks in the surrounding areas. Much more work must be done before a comprehensive tectonic reconstruction of the larger southwestern region can be accomplished for Neogene time.

- 3) Relatively few detailed paleomagnetic studies have been carried out in the Mojave Desert. The area of available paleomagnetic data closely coincides with the

interpreted zone of deformation. This coincidence is due to no information to the south of the inferred southern boundary of deformation and little information from rocks north of the deformation zone. This problem is simply due to a paucity of paleomagnetic data and is mitigated by evidence on both sides of this zone for undeformed pre-Tertiary structural features.

### **Predictions of the Reconstruction**

The above reconstruction predicts that rocks older than ~20 Ma found in a broad E-W band across the Mojave Desert and the southern Sierra Nevada should have experienced early Miocene clockwise rotation and E-W dextral translation. This implies that outside of this zone, clockwise rotations of early Miocene age should not be present. The reconstruction predicts the approximate boundaries of this rotation to the north and south, which have been displaced across the younger dextral tectonic regime in the Mojave Desert and the sinistral Garlock fault. The eastward extent of this deformation is not addressed by this simple reconstruction, but this deformation likely diminishes or is incorporated into regional extension to the east. Activity of the Colorado River extensional corridor spans the right age and approximately the correct magnitude (Davis and Lister, 1988) to explain the offset on this E-W shear. To the west, the effects of this tectonic event must have been translated north-westward by the San Andreas fault. This reconstruction assumes that pre-Miocene structural and tectonic features were originally linear and continuous through the Mojave Desert. The continuation of these pre-Miocene features is predicted to have been transported between 60 km and 90 km dextrally across the area of deformation. All of these predictions can be tested by future study of the location of pre-Miocene features and the rotational history of rocks surrounding this proposed zone of deformation.

## **Driving Mechanism**

The timing and amount of this proposed regional shear suggests that this deformation should ultimately be referred to in a plate tectonic context. Evidence for this connection lies in timing and kinematics of the passing of the Mendocino fracture zone. The Mendocino fracture zone (MFZ) is a transfer zone along which strike-slip motion accumulated due to the offset of the Pacific-Farallon spreading center along this structure. Because there was a difference in age of the oceanic lithosphere juxtaposed across the MFZ, this structure also reflects a thermal-mechanical boundary along this line. When the spreading center south of the MFZ ceased production of oceanic material, either a slab gap or a slab window was created due to cessation of subduction of that portion of the Farallon plate (Figure 4.10; Severinghaus and Atwater, 1990). The portion of the Farallon plate north of the MFZ (now the Juan de Fuca plate) continued to be subducted, with the MFZ representing the southern boundary to this plate. The thermal-mechanical boundary along this line was substantial, with a cold slab subducting to the northeast whereas there was no slab immediately to the south. A semantic question can be asked as to whether any subducted plate or boundary may still be referred to by the same name which it was given when at the earth's surface. Below I will use MFZ both before and during subduction for the following reasons:

- 1) It is implicit in the reconstruction of plate positions, configuration, and boundaries that if a plate or boundary has been consumed by subductive action, we can pull it back out of the subduction zone (by reconstruction) without changing its name (see Atwater, 1970; Engebretson and others, 1985; Atwater, 1989; Stock and Molnar, 1988; Severinghaus and Atwater, 1990).
- 2) The boundary which appears as the MFZ today existed in the past and the rocks associated with it have been subducted beneath the North American continent.

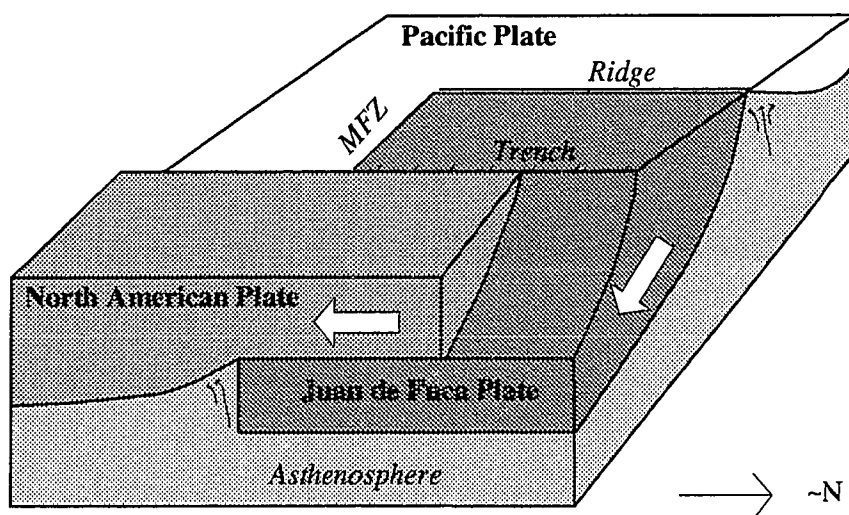


Figure 4.10. Block diagram of Miocene to present relative plate motions. A slab gap formed south of the Mendocino fracture zone (MFZ) is shown moving north relative to the North American plate. White arrows designate relative motion with respect to the Pacific plate. Small arrows show possible motion within the asthenosphere. After Lachenbruch and Sass (1980).



- 3) The MFZ is a boundary readily recognized throughout the geological community and to give the same boundary a new name merely because it has been subducted would introduce avoidable confusion and would counter the precedents set by previous authors (Atwater, 1970; Glazner and Bartley, 1984; Glazner and Loomis, 1984; Loomis and Glazner, 1986).

In the remainder of this paper, I will use "MFZ" to denote a thermal-mechanical boundary located at the southern edge of the Juan de Fuca plate and not the actual fault zone for those portions which have been subducted.

Atwater (1970) initially recognized that late Tertiary changing plate interactions from subduction to transform must have coincided with changes in the geology of southern California. Many authors have shown that during Miocene time the Mendocino triple junction and the MFZ migrated from south to north past the Mojave Desert (Atwater, 1970; Engebretson and others, 1985; Stock and Molnar, 1988; Severinghaus and Atwater, 1990). Severinghaus and Atwater (1990) show that between 30 Ma and 20 Ma, oblique subduction was carrying Juan de Fuca plate, and the MFZ, under North America at ~45 mm/yr toward ~N50E (calculated from Atwater, 1989). This subduction caused the MFZ to migrate northward at up to ~30 mm/yr. The eastward component of this subduction was ~30-35 mm/yr. Frictional coupling between the subducting Juan de Fuca plate and the overriding North American plate produced a compressional force on the North American plate which would not be found south of the MFZ.

Early Miocene regional extension was oriented ~N-S as suggested by kinematic indicators (after removal of subsequent clockwise rotation) which indicates a least compressive stress oriented horizontal and ~N-S. As northward migration of the ~E-W oriented MFZ progressed, an area under the North American plate developed where no oceanic plate existed (Figure 4.10). This area would have been exposed directly to the

asthenosphere which would have risen to fill the gap left by the moving plate, reducing the N-S horizontal stress and possibly achieving a N-S tensile stress at the base of the North American plate. Also, south of the MFZ, the Pacific-Farallon spreading center stalled and ceased production of new oceanic material as it came close to the subduction zone, changing the convergent boundary along the North American plate into a transform boundary with the Pacific Plate. Sevringhaus and Atwater (1990) show that spreading associated with the broken pieces of the Farallon plate between the Mendocino and Murray fracture zones continued to as late as 20 Ma. This spreading indicates that subduction was still occurring, therefore compressive forces were still active up to that time. This ~E-W compression may have produced a buttressing effect which would preclude any eastward component of extension. As spreading south of the MFZ ceased, this E-W buttress was no longer present, allowing a dextral shear couple to be established concentrated by the recently extended crust.

A look at the relative motions of the Pacific, Farallon and the North American plates during early Miocene time provides insight into the tectonic forces that are compatible with E-W oriented dextral shear. Figure 4.11 shows the relative motion circuit calculated from data presented by Engebretson and others (1985). As subduction ceased along the southern California coast, the northeast compression (Farallon motion) ceased in the North American plate, either allowing or promoting southeastward relaxation (or possibly tension). Tectonic plates typically transmit some component of their convergence to the overriding plate through frictional coupling, hence we observe compressional earthquakes at subduction zones. This frictional coupling may have been increased as the Juan de Fuca plate subducted under the thick, rigid beam of the Sierra Nevada batholith. If one assumes perfect coupling with the North American plate, then the relative forces across the MFZ are nearly E-W, as described by the Pacific - Farallon motion (Figure 4.11), with a magnitude of ~60 km/my of E-W dextral shear that could

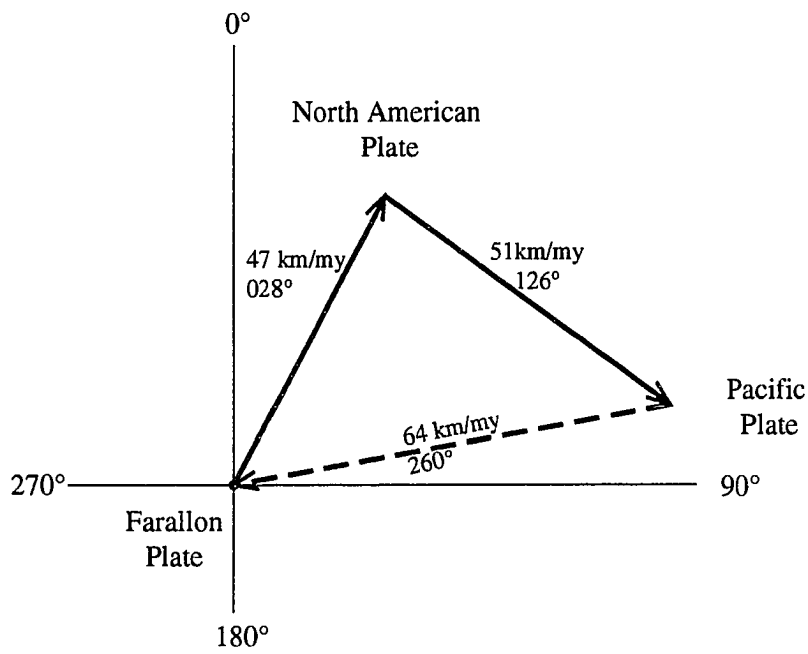


Figure 4.11. Relative plate motion vector circuit for early Miocene time. The Pacific, North American and Farallon plates between 28-17 Ma as calculated from data of Engebretson and others (1985).

be accommodated by this motion. Although it is probably not valid to assume 100% coupling of the plates involved, the offset predicted by the proposed model for this shear could be accommodated in ~2 my by 50-60% coupling. The Pacific and North American plates also need not be physically coupled, for after cessation of Pacific-Farallon subduction, the remnant of the Farallon plate would move away from the North American plate along the Pacific-North American vector allowing North America to move in to fill the void.

### **Alternative Explanations for Clockwise Rotation**

The preferred model to explain early Miocene clockwise rotation in the Mojave Desert entails development of an E-W zone of dextral. This shear is interpreted to have been concentrated by the immediately previous crustal extension and to have driven by subduction of the MFZ. Other possibilities exist which may explain the observed rotations:

1) Each of these rotations may be independent phenomena due to local rotations of crustal blocks. Little is known about the transformation of Farallon plate subduction to Pacific plate strike-slip interaction. It may be that as this change took place, dextral strike-slip faulting affected the continental plate boundary. This faulting could have driven local crustal rotations as is occurring at present in the Mojave Desert. However, the rotation of large coherent blocks such as the southern Sierra Nevada would create large space problems if they were rotating independently from surrounding rocks.

2) If the assumption of continuous, linear pre-Miocene structural features is not valid, then another process may have been active. If an oroclinal bending occurred, then a structure or set of structures must have developed to mitigate space problems of

rotating large volumes of crust. None are suggested by the mapped geology of this region.

3) This area may have rotated due to differential extension. If crustal extension was taking place to the east and west of this area, a shear zone to accommodate differences between amounts or direction of extension may have resulted. Potential candidates for these extensional systems could be the Colorado River extensional system to the east and the southern Sierra Nevada extension to the west (Goodman and Malin, 1992). The timing of these extensional events may not be close enough to support this hypothesis, for the Peach Springs tuff is affected by extension in the Colorado River extensional corridor, but is not affected by extension or rotation in the Mojave extensional belt.

The preferred model of an E-W zone of penetrative shear encompasses several independent geological features and data sets, and explains the deformation adequately.

### **Previous Models Linking Plate Motions and Continental Tectonics in Southern California**

Atwater (1970) and Engebretson and others (1985) predicted that tectonic events on the North American plate should be linked to the change from a subduction to transform tectonics in Neogene time. Bartley and Glazner (1984) suggested that changing plate interactions were responsible for widespread early Miocene volcanism in the southwest. This is quite compatible with the model proposed above. Glazner and Loomis (1984) and Loomis and Glazner (1986) proposed a causal relationship of the passing of the Mendocino fracture zone and the evolution of sedimentary basins in southern California. Their model called for the N-S opening of sedimentary basins, with accompanying extensional faulting. This is very similar to the plate-boundary-driven regional extension proposed in this paper, except on a smaller scale. Their data suggesting N-S

extension within the Mojave Desert is suspect due to the recently recognized evidence for regional clockwise rotation, whereas their evidence north of the Garlock fault may still be appropriate. Glazner and Loomis (1984) portrayed the reconstructed position of the MFZ without the appropriate large errors associated with such a reconstruction, therefore their concordance of the passage of the MFZ and changes in sedimentation may or may not be significant. Their basic idea of a causal relationship between the passage of the MFZ and changes in tectonics and sedimentation is probably valid.

Kanter and McWilliams (1982) proposed a model for the oroclinal bending of the southern Sierra Nevada which involved Paleocene regional rotation. They also suggested many alternatives which included rotation due to plate interactions and specifically mentioned the proximity of the Mendocino fracture zone and the possibility of the rotation to be caused by distributed shear at that time. With more complete data, McWilliams and Li (1985) suggested that early Miocene plate interactions had probably driven the rotation and that the "tectonic snow plow" of the passing of the Mendocino triple junction could have been the causal mechanism. These proposed mechanisms are similar to the model proposed in this paper.

Bartley and Glazner (1991) proposed that rotation in the central Mojave Desert was produced by two *en echelon* extensional systems opening simultaneously with the overlapping area rotating clockwise. Their model requires that there is no structural break between the overlapping extensional areas in order to produce the rotation. The major problem with this model is that it calls for rotation synchronous with extension and differential extension between rocks in the upper and lower plates of extension. Both of these predictions are not supported by paleomagnetic and kinematic data (see Chapter 3). Martin and others (1993) noted apparent offsets of pre-Tertiary structural and stratigraphic features and speculated that the offset is due to a transfer fault linking the Colorado River and Mojave extensional systems, basing their interpretations on the

model of Bartley and Glazner (1991). However, their speculation contradicts the model of Bartley and Glazner (1991) which involves a large amount of crust rotating between two extensional systems. If this area were to be cut by a transfer fault, the difference in extension would be accommodated by translation and not rotation.

Martin and others (1993) proposed an E-W dextral strike-slip fault to explain evidence for deformation of pre-Tertiary structural features. They speculate on the location of this proposed structure, but acknowledge that as yet there exists no candidate for this fault and that evidence for early Miocene motion is lacking. Their model does not explain clockwise rotations indicated by the available paleomagnetic data, nor information which suggests that the rotation occurred in early Miocene time, after the major phase of regional extension.

## CONCLUSIONS

Many models have been proposed which predict or explain vertical-axis rotations in the Mojave Desert and surrounding areas. Paleomagnetic studies in the Mojave Desert block suggest a complicated array of clockwise, counter-clockwise and null rotations which may be separated to some extent by age. Geometric models for late Miocene and younger regional counter-clockwise rotation proposed by Garfunkel (1974) are not supported by the present data, whereas some data supports clockwise rotation as proposed by Luyendyk and others (1980) and Carter and others (1987), but appears more complex than these models predict. As concluded in Chapter 3, the models by Bartley and Glazner (1991) and Valentine and others (1993) proposing regional rotation directly associated with extension are not supported by data presented in this dissertation that indicate that rotation occurred after the major phase of extension.

Clockwise deflected paleomagnetic directions in the central Mojave Desert block and in the southern Sierra Nevada indicate an early Miocene regional clockwise

rotational event. When these areas of rotation, along with the traces of pre-Tertiary structural features, are reconstructed by removing late Miocene and younger deformation, they become aligned in an ~E-W-trending band. This band is interpreted as a dextral shear which was active in early Miocene time and created a regional orocline with the rocks affected showing clockwise rotations. The dextral shear is proposed to have been driven by stresses created by the subduction of the thermal and mechanical boundary present at the southern boundary of the Juan de Fuca plate.

This model provides an explanation for paleomagnetic data indicating a regional clockwise rotation and is compatible with proposed pre-Miocene features (Last Chance thrust system, Eastern California thrust system and the Independence dike swarm) continuing through the Mojave Desert. The oroclinal bend in the southern Sierra Nevada is also given a tectonic mechanism and related to regional tectonism. The proposed tectonic mechanism for the E-W shear couple implies that the Mendocino fracture zone was at ~ 35°N latitude at ~19 Ma with respect to stable North America. This model makes several predictions which can be tested by future work: 1) Clockwise early Miocene rotations should be confined to an area bounded on the north and south, 2) About 60-90 km of E-W dextral shear is accommodated by the zone, and 3) Pre-Miocene structural features will be displaced as they cross this zone. This model has major implications for Mesozoic and Paleozoic paleogeographic reconstruction of the southern Cordillera and also provides a pinning point (time and location) for the Mendocino fracture zone in its northward sweep along North America.



## **CHAPTER 5 - SUMMARY**

The southwest Cady Mountains contain stratigraphic and structural relationships which help constrain the nature and timing of tectonic events which affected the Mojave Desert block and adjacent areas during Neogene time. The overall objective of this study has been to investigate the relationship between regional extension and regional rotation in the Mojave Desert. This objective is approached by determining the tectonic history for the southwest Cady Mountains and applying that history to the region. In this chapter, a summary of new data is presented and evaluated to interpret a tectonic history for the southwest Cady Mountains. This history is then combined with regional data to explore the implications of this study on aspects of regional extension and rotation.

### **GEOLOGY OF THE SOUTHWEST CADY MOUNTAINS**

The southwest Cady Mountains comprise three late Tertiary (upper Oligocene to middle Miocene) volcanic and sedimentary units deposited on a pre-Tertiary granitic basement. This basement is dominantly granite which often displays rapakivi texture. The granite is cut locally by small aplitic intrusions. The age of this granite is uncertain, for K-Ar geochronology (hornblende) from similar nearby granites give Mesozoic ages, but regionally, rapakivi texture is associated with a suite of ~1.4 Ga anorogenic granites. A U-Pb age on zircon from this granite should define its magmatic age.

The formation of Poe was deposited upon the granitic rocks over an erosional unconformity. These volcanic tuffs, flows and lahars are currently dipping up to ~60° and their dips shallow upward to about 40°, indicating either tilting synchronous with deposition (growth-fault geometry) or substantial initial dip which shallows over the time of deposition. Stepwise  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology on biotite from a tuff at the

base of the Poe section displays a disturbed release pattern, but the total gas age suggests that deposition may have started as early as late Oligocene time ( $28.1 \pm 1$  Ma). Paleomagnetic data from these rocks indicates that some of the breccia units were deposited at elevated temperature (consistent directions in conglomerate test) while some breccias appear to have been deposited at low temperature (random directions in conglomerate test). Some paleomagnetic data from the Poe rocks show inclinations which become close to that of the early Miocene reference direction after tectonic correction, suggesting that their characteristic magnetizations were acquired prior to tilting of the strata, arguing against a substantial initial dip for these rocks. The paleomagnetic data interpreted to represent primary magnetizations suggest that these rocks have rotated clockwise  $127^\circ \pm 30^\circ$  since their deposition.

The formation of Poe rocks are cut by at least two faults which do not affect overlying units. One fault strikes NE and shows normal offset, whereas the other fault strikes NW and shows right lateral offset. The NW-striking fault is a zone ~20 m in width in which sub-horizontal grooves and slicken striae are found along planes striking similar to the zone. No kinematic indicators were found on the plane of the NE-striking fault. The NW-striking fault offsets the basement/formation of Poe contact ~ 0.7 km in a dextral sense and bends Poe strata higher in the section. From this information, these faults are interpreted to be a normal fault (NE-strike) and a dextral transfer zone (NW-strike) that were active during and helped accommodate early Miocene extension.

The formation of Troy Peak was deposited unconformably on the formation of Poe. These rocks consist of a basal monolithologic tuff breccia overlain by basalt flows. In the northern portion of the area, the section continues upward with additional andesitic to basaltic flows and breccias, whereas the lower basalts are directly overlain by sediments of the "Barstow Formation" to the south. A total fusion  $^{40}\text{Ar}/^{39}\text{Ar}$  date on hornblende from the basal tuff breccia suggests that deposition of the formation of

Troy Peak initiated in late Oligocene time ( $26.6 \text{ Ma} \pm 1.7 \text{ Ma}$ ). Sanidine and biotite separated from a welded tuff in the northern section of the formation of Troy Peak yield identical  $^{40}\text{Ar}/^{39}\text{Ar}$  total gas ages and overlapping plateau ages, indicating that deposition lasted until at least  $\sim 18.6 \text{ Ma}$ .

The formation of Troy Peak strata do not display the same style of tilting as that of the formation of Poe. The formation of Troy Peak has been folded into a west-plunging antiform. Basalt flows on both limbs of this fold display strong, well-grouped magnetizations which pass a fold test and suggest  $130^\circ \pm 14^\circ$  of clockwise rotation since deposition. These rocks are interpreted to have been deposited after the major portion of extension was complete in the southwest Cady Mountains.

The "Barstow Formation" was deposited conformably on the formation of Troy Peak and crops out in the southern portion of the study area. These rocks consist mainly of volcanoclastic siltstones and sandstones with occasional tuff and conglomeratic beds. A fossil horse tooth from Merychippus cf. M. carrizoensis found near the base of this section indicates that deposition of the "Barstow Formation" began around 16 Ma. Two  $^{40}\text{Ar}/^{39}\text{Ar}$  dates on biotite separated from tuffs in this formation are also compatible with a middle Miocene age for these sediments ( $17.6 \text{ Ma} \pm 0.2 \text{ Ma}$  total fusion age and  $14.0 \text{ Ma} \pm 0.3 \text{ Ma}$  plateau age).

The "Barstow Formation" strata have attitudes similar to the basalts of the underlying formation of Troy Peak, which has been folded into an antiform. The contact between the formation of Troy Peak and the "Barstow Formation" is cut by a few minor faults. Because of the angular conformity, the faulting and folding deformations are interpreted to have occurred younger than 14 Ma, after deposition of the "Barstow Formation". Paleomagnetic data from the "Barstow Formation" indicate that  $67^\circ \pm 15^\circ$  of clockwise rotation has affected these rocks since they were deposited.

These data also indicate that  $63^{\circ} \pm 20^{\circ}$  of clockwise rotation affected the southwest Cady Mountains prior to ~ 16 Ma, initiation of deposition of the "Barstow Formation."

## **TECTONIC HISTORY**

The observations and interpretations presented above can be combined into a Neogene tectonic history for the southwest Cady Mountains. This history will be presented as a sequence of tectonic events, pointing out their structural and stratigraphic manifestations. Three main tectonic events are recognized: 1) extension, 2) clockwise rotation, and 3) folding, faulting and rotation. The third tectonic event is a combination of tectonic occurrences which all happened sometime younger than 14 Ma, but cannot be separated reliably in their sequence.

### **Extension**

The formation of Poe was deposited during a phase of crustal extension. The major normal and transform faults are interpreted to have been involved in and facilitated this extension. The decrease in stratal tilt combined with paleomagnetic data indicate that deposition was at least partly synkinematic with the extension. According to the isotopic ages presented in this study, this extension occurred younger than ~28.1 Ma, the age of the basal tuff of the formation of Poe, and the tilting due to extension was complete by ~26.6 Ma, when the overlying tuff breccia and basalts of the formation of Troy Peak were deposited. The agreement in mean paleomagnetic directions for the formations of Poe and Troy Peak imply that during tilting due to extension, no vertical axis rotation occurred.

The isotopic dates obtained in this study suggest that tilting of strata due to extension in the southwest Cady Mountains is occurred between ~28.1 Ma and ~26.6 Ma. This is not consistent with the data and interpretation of Dokka (e.g., 1989) which call for regional extension between ~22 Ma to ~20 Ma. The ages interpreted for the

rocks from the formations of Poe and Troy Peak are the oldest ages attributed to Tertiary volcanic rocks from the Mojave Desert Block. These ages are also somewhat suspect in that the 28.1 Ma age is calculated from the total gas release from biotite which had a very disturbed release pattern, and the 26.6 Ma age is a single fusion age on hornblende. These ages are not extremely reliable, yet suggest that more detailed geochronology should be considered in order to clarify this discrepancy.

### **Clockwise Rotation**

Paleomagnetic data suggest that rocks belonging to the formations of Poe and Troy Peak experienced  $\sim 130^\circ$  of clockwise rotation since their deposition. Because paleomagnetic data suggest that rocks of the "Barstow Formation" have only experienced  $\sim 67^\circ$  of clockwise rotation since their deposition,  $\sim 63^\circ$  of clockwise rotation must have occurred between  $\sim 26.6$  Ma (the age of the Troy Peak tuff breccia) and  $\sim 16$  Ma (the age of the exposed base of the "Barstow Formation"). This rotation occurred after the tilting of the formation Poe had ceased, implying that the rotations were two separate tectonic events. This early Miocene rotation is interpreted to have been driven by an  $\sim$ E-W dextral shear produced by the interaction of the subducting MFZ and the overriding North American plate.

### **Folding, Faulting and Rotation**

The outcrop and structural pattern of the formation of Troy Peak describes a breached antiform. Because the basal strata of the "Barstow Formation" lie at the same attitude as the Troy Peak basalts which they overlie, this folding is interpreted to have happened sometime after the "Barstow Formation" was deposited. Faults with small offsets cut all three formations, also indicating tectonic activity younger than the "Barstow Formation". Paleomagnetic data from rocks of the "Barstow Formation" are interpreted to indicate that  $\sim 67^\circ$  of clockwise rotation has affected this area since  $\sim 14$  Ma.

The rotation is proposed to be driven by dextral strike-slip motion on the bounding Calico and Pisgah faults. If this is correct, then the southwest Cady Mountains are probably currently undergoing active rotation, for the Calico and Pisgah faults are seismically active. The faulting, folding, and rotation may or may not all be related to the same tectonic event. There is no available information with which to determine their relationships.

### **IMPLICATIONS FOR DEVELOPMENT OF EARLY MIOCENE EXTENSION.**

The southwest Cady Mountains contain structural and stratigraphic relationships which have counterparts in the rest of the Daggett extensional terrane of the Mojave extensional belt. These relationships include stratal tilt of the formation of Poe (NW), normal faulting (NE strike) and strike-slip faulting (NW strike); all relationships indicate NW-SE directed extension. Analogous structures in the remainder of the Daggett terrane are consistent with SW-NE extension with strata dipping to the SW. If the post-"Barstow Formation" clockwise rotation is removed, then the extension direction interpreted from structures of the southwest Cady Mountains moves to NE-SW with the stratal dip to the SW, in agreement with the direction interpreted from structures of the Daggett terrane. The remainder of the rotation also matches fairly closely the rotation for the analogous rocks of the Daggett terrane reported by Ross (1988) and Ross and others (1989).

The present orientation of structures in both the upper and lower plates of the Mojave extensional belt indicate that extension was directed ~NE-SW. These structures include those of the Daggett terrane. If the extensional structures of the southwest Cady Mountains are rotated counter-clockwise in order to remove the total of ~130° of clockwise rotation which has occurred since their formation, they become oriented to

indicate an ~N-S extensional direction. Removing the reported rotation (~50° clockwise; Ross and others, 1989) from the remainder of the Daggett terrane also aligns structures to indicate an original ~N-S extensional direction. Because structures in every terrane, in both the upper and lower plates, indicate the same extensional direction, it is most likely that none of these terranes have rotated with respect to each other, and that the upper plate rocks have not rotated with respect to the lower plate rocks. The rotation of the Daggett terrane therefore indicates that the entire extensional belt has been rotated clockwise. This rotation represents a previously unappreciated early Miocene regional tectonic event.

### **REGIONAL CLOCKWISE ROTATION**

When the available paleomagnetic data are separated into groups according to age, implied rotations which are demonstrably older than ~18 Ma are all clockwise in nature. If the recent deformation relating to right-lateral shear through the Mojave Desert block is removed (following Dokka and Travis, 1990a), then the areas interpreted to have experienced early Miocene clockwise rotation all become aligned in an ~E-W trending band. This band includes the area affected by the oroclinal bend of the southern Sierra Nevada. The Paleozoic and Mesozoic structures which have been proposed to continue through the Mojave Desert block appear offset in a right-lateral manner. The oroclinal bend of the southern Sierra Nevada also suggests movement in a right-lateral manner, as does the clockwise direction of rotation. When right-lateral shear is removed from this zone, the proposed pre-Tertiary elements become aligned with their counterparts on the other side of the shear zone.

The Mendocino fracture zone, in early Miocene time, represented a thermal and mechanical boundary between a thick older subducting oceanic plate to the north and a younger, diffuse plate (or possibly no plate at all) to the south (Severinghaus and

Atwater, 1990). Frictional coupling between the subducting and overriding plates would produce forces in the North American plate north of the MFZ which would not be produced to the south due to no subduction there. The change of forces across the subducting MFZ could produce an ~E-W dextral shear couple in the North American plate. In addition, one would expect much more heat flow to the base of the North American plate south of the MFZ due to the lack of insulation from a cold subducting slab which may have facilitated regional volcanism and extension.

The existence of an orocline in the Mojave Desert is not a new concept, having been proposed by Burchfiel and Davis (1980), Kanter and McWilliams (1982) and again by Golombek and Brown (1988). Ideas of relating plate tectonic events to deformation in southern California is also not original. Kanter and McWilliams (1982) suggested the possibility of their proposed deformation having been driven by forces related to subduction. The passage of the Mendocino fracture zone (or triple-junction) has been proposed to have been responsible for low-angle normal faulting and volcanism (Glazner and Bartley, 1984) and the creation of sedimentary basins and changes in drainage patterns (Glazner and Loomis, 1984; Loomis and Glazner, 1986). The concepts provided by these previously proposed models are not necessarily in conflict with the model proposed in this study, however, since their proposal, much more information has been obtained which is not explained by them. In particular, recent paleomagnetic studies suggest that substantial clockwise rotation has taken place which would have also rotated features indicating sedimentary transport direction. The difference between previously proposed models for rotation or oroclinal bending and the model proposed here is that there is much more paleomagnetic data to constrain the mechanism and area of deformation and that here the cause is proposed to be a specific structure; namely an ~E-W striking right-lateral zone of distributed shear.



## CONCLUSIONS

This study presents evidence for a previously under-appreciated Neogene tectonic event in the Mojave Desert block and other portions of southern California. This study demonstrates that early Miocene clockwise regional rotation occurred after regional extension and that this rotation most likely affected all of the Mojave extensional belt. The patterns of paleomagnetic data and pre-Tertiary structures after removal of post-rotation strike-slip deformation, indicates that the tectonic structure could have formed within a regional ~E-W band of right-lateral shear. This shear may have been caused by a mechanical change in subduction across the Mendocino fracture zone and interaction with the over-riding North American plate.

## RECOMMENDATIONS FOR ADDITIONAL STUDY

Although this study adds significantly to our understanding of the early Miocene development of the Mojave Desert, clearly more work is needed. The model derived in Chapter 4 should be testable with carefully selected studies elsewhere in the Mojave Desert block. In particular, the proposed pre-Tertiary structural elements of the Paleozoic Last Chance thrust system, the Mesozoic eastern California thrust system and the Mesozoic Independence dike swarm should be better defined and other areas tested for early Miocene rotation. All parts of the Mojave extensional belt should show a history of early Miocene clockwise rotation, which is potentially testable. The absolute timing of this rotational event remains poorly constrained, and new isotopic data presented here suggest that more work should be done on the initiation of volcanism in the Mojave Desert and on the absolute timing of regional extension.

The array of paleomagnetic data produced to date in the Mojave Desert block is somewhat baffling. The counterclockwise rotations in the western Mojave Desert block are not well understood in terms of their geologic context, nor well bracketed in age. It

is obvious that careful tectonic investigations need to be done in order to understand better both the early Miocene clockwise rotation and rotations driven by the present strike-slip deformation.

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## **APPENDIX A - GEOCHRONOLOGY OF THE SOUTHWEST CADY MOUNTAINS**

### **INTRODUCTION**

Six samples from different units that crop out within the southwest Cady Mountains were collected during the spring of 1991. These samples were collected from tuffaceous units in the formation of Poe (1), the formation of Troy Peak (2), and the "Barstow Formation" (2). These were chosen for their fresh appearance and for minerals which were likely to be amenable to age determination using  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronologic methodology. Thin sections of each sample were prepared and studied for possible alteration.

Samples were prepared by crushing with a jaw crusher and then pulverized in a disc mill. The material was then passed through a standard sieve stack (60, 80, 100, 120 and 180 mesh). The 80 mesh portion was washed repeatedly with tap water until the effluent was clear. This washed sample was allowed to dry and then the highly magnetic fraction was removed with a hand magnet. The less magnetic fraction was passed repeatedly through a Franz magnetic separator, varying the magnetic field and the slope of the track to obtain fairly pure mineral separate. Samples yielded separates of biotite, sanidine or hornblende. Biotite was separated easily with the Franz, and the remaining impurities were removed by shaking the mineral off of a piece of paper (prismatic impurities tend to roll, whereas mica tends to stick to the paper) and by hand-picking using a binocular microscope and a wet brush hair.

The sanidine was obtained from the least magnetic fraction of its sample. This fraction was then subjected to a heavy liquid (sodium penta-tungstate) in order to remove any possible plagioclase. The light fraction was washed and remaining impurities were removed by hand-picking. Hornblende was the most difficult to

separate from its parent material. A population of mixed pyroxene and magnetite contained the same magnetic and density properties. After repeated magnetic and heavy liquid separation, the most pure fraction was about 60% hornblende. A small amount of pure sample was produced by hand-picking.

The sample separates were sent to Dr. Daniel Lux at the University of Maine, Orono for preparation for irradiation. The samples were irradiated ending March 9, 1992 and were analyzed at Dr. Lux's laboratory in Orono between May 23 and May 26 by the author. Two samples (the hornblende and one biotite) were too small for a stepwise release regimen and were taken directly to fusion. The remaining samples were subjected to 10 or more heating steps in order to better evaluate their mineral stability. Two biotite samples and the sanidine sample yield plateau ages.

**SAMPLE 910075**

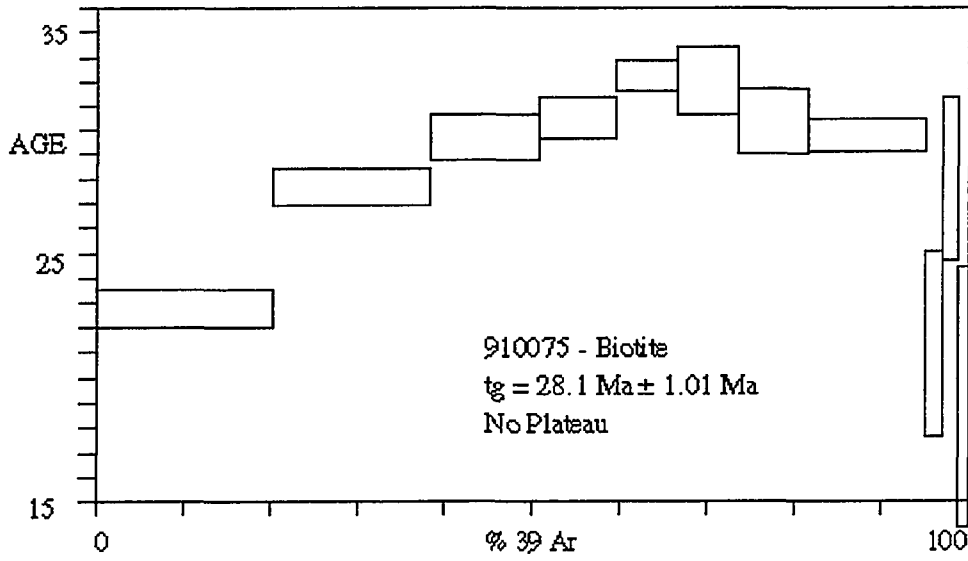
910075-B J = .010357.

Biotite separate.

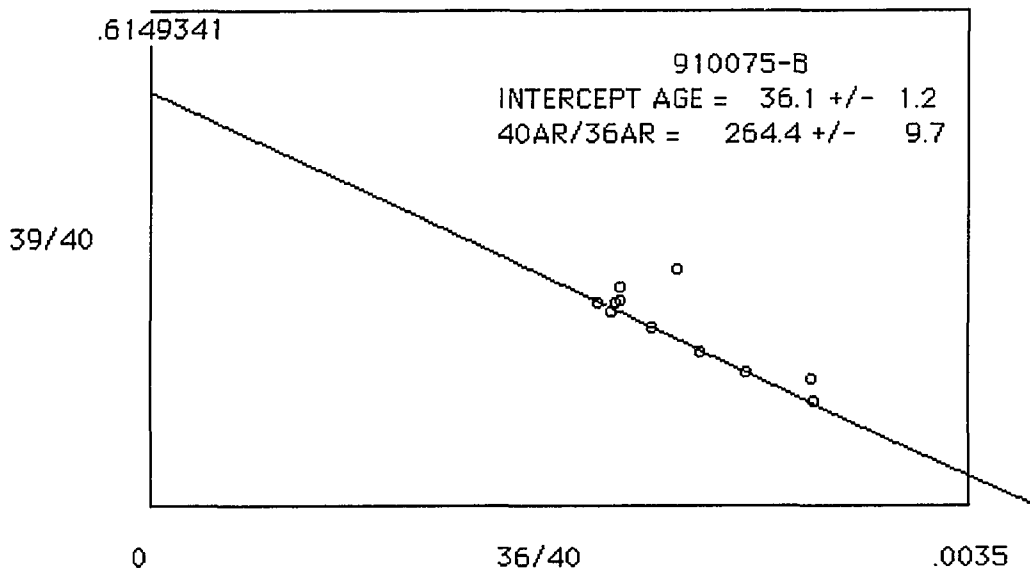
Table A.1  $^{40}\text{Ar}/^{39}\text{Ar}$  release Data for sample 910075.

Temp (°C)	40/39	37/39	36/39	Moles 39	%Total	% Radiogenic	K/Ca	AGE (Ma)
750	7.665	0.064	0.0218	445.6	20.3	16.0	7.60	22.78 ± 0.73
840	6.029	0.063	0.0153	395.0	18.0	24.8	7.73	27.70 ± 0.76
930	5.256	0.062	0.0123	276.6	12.6	30.5	7.93	29.74 ± 0.94
1000	4.530	0.057	0.0097	191.5	8.7	36.3	8.58	30.49 ± 0.85
1050	4.181	0.061	0.0082	154.3	7.0	41.7	8.00	32.25 ± 0.61
1100	4.000	0.097	0.0077	153.0	7.0	43.2	5.05	32.02 ± 1.42
1150	3.983	0.129	0.0079	174.9	8.0	41.1	3.80	30.34 ± 1.34
1200	3.957	0.126	0.0079	297.9	13.6	40.6	3.90	29.80 ± 0.68
1250	3.445	0.108	0.0077	43.2	2.0	33.4	4.55	21.35 ± 3.71
1300	3.725	0.111	0.0075	41.2	1.9	40.5	4.41	28.00 ± 3.33
FUSE	6.279	0.133	0.0177	25.3	1.1	16.5	3.70	19.21 ± 5.25
Total				2198.5	100.0			28.10 ± 1.01





A.1A



A.1B

Figure A.1  $^{40}\text{Ar}/^{39}\text{Ar}$  plots for sample 910075. A shows the  $^{40}\text{Ar}/^{39}\text{Ar}$  release spectrum and B shows an isochron plot for sample 910075.

**SAMPLE 910076**

910076-B                                      J = .010372.

Biotite separate.

Table A.2 <sup>40</sup>Ar/<sup>39</sup>Ar release Data for sample 910076.

Temp (°C)	40/39	37/39	36/39	Moles 39	%Total	% Radiogenic	K/Ca	AGE (Ma)
FUSE	2.498	0.074	0.0052	609.1	50.0	37.8	6.59	17.57 ± 0.26

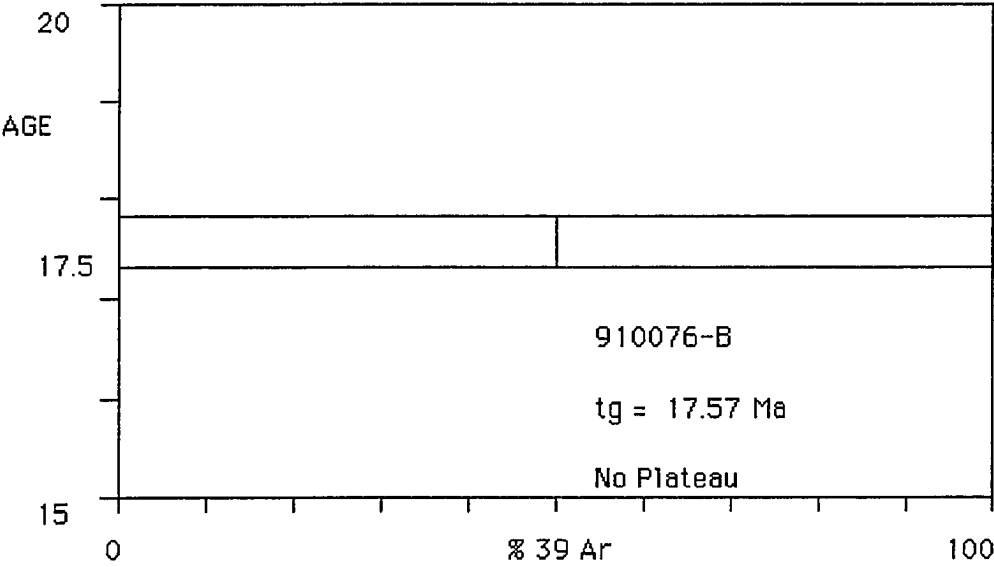


Figure A.2 <sup>40</sup>Ar/<sup>39</sup>Ar release spectrum for sample 910076.

**SAMPLE 910077**

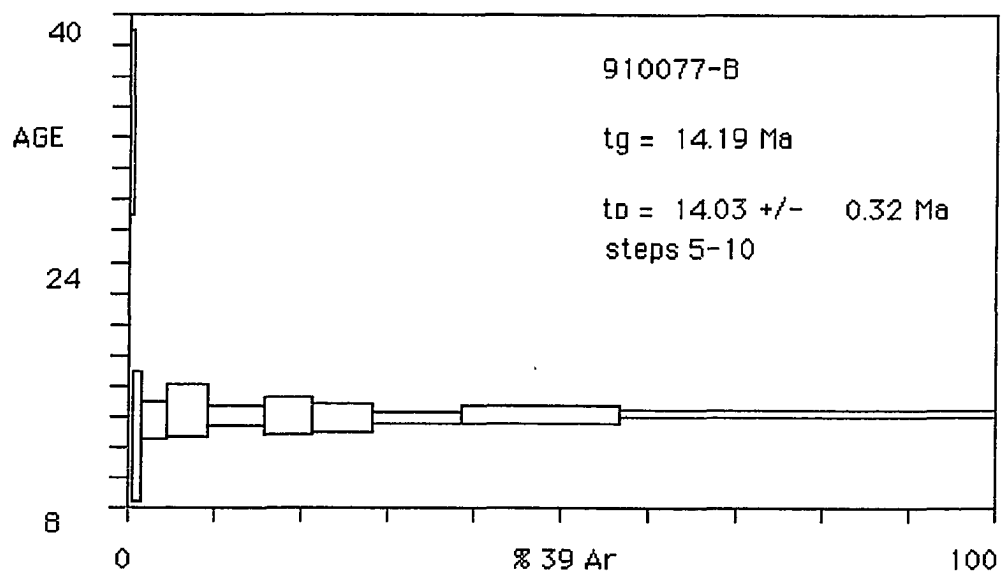
910077-B

J = .010301.

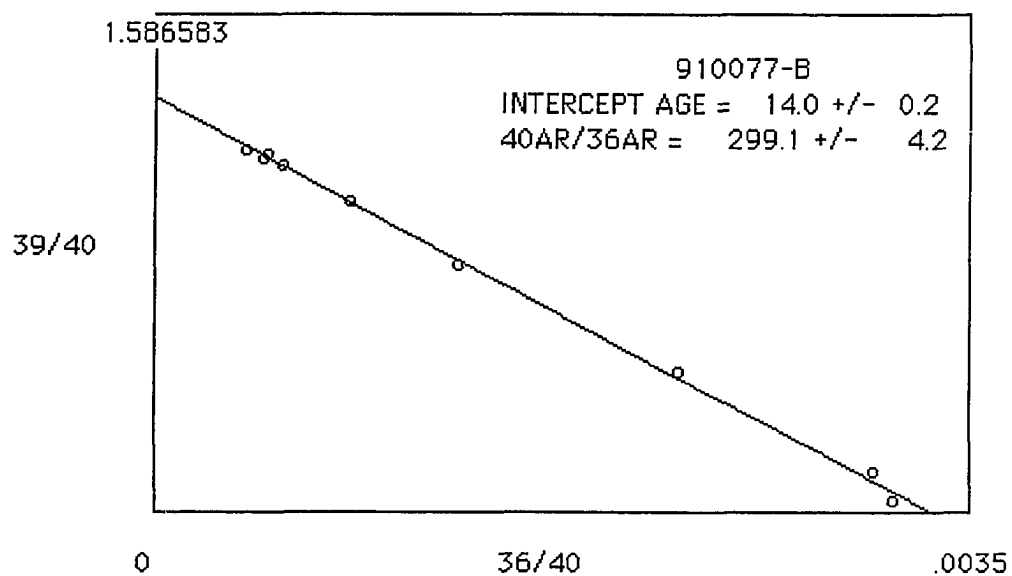
Biotite separate.

Table A.3  $^{40}\text{Ar}/^{39}\text{Ar}$  release data for sample 910077.

Temp (°C)	40/39	37/39	36/39	Moles 39	%Total	% Radiogenic	K/Ca	AGE (Ma)
660	29.014	0.059	0.0921	17.3	0.5	6.2	8.25	33.03 ± 6.03
750	7.825	0.026	0.0241	3.33	1.0	8.7	18.81	12.66 ± 4.26
840	2.234	0.011	0.0050	93.8	2.9	33.3	43.98	13.77 ± 1.26
930	1.280	0.009	0.0016	151.6	4.8	60.7	54.90	14.38 ± 1.68
1000	1.023	0.007	0.0008	202.8	6.4	74.1	68.91	14.04 ± 0.61
1050	0.919	0.008	0.0005	174.9	5.5	82.3	62.96	14.01 ± 1.18
1100	0.892	0.007	0.0004	228.8	7.2	84.1	68.77	13.89 ± 0.89
1150	0.892	0.009	0.0004	325.9	10.2	84.1	54.28	13.89 ± 0.36
1200	0.881	0.013	0.0003	581.2	18.2	86.9	38.61	14.17 ± 0.56
FUSE	0.904	0.019	0.0004	1377.2	43.2	84.7	25.24	14.16 ± 0.18
Total				3186.7	100.0			14.19 ± 0.58
Plateau age	[1000	FUSE]						14.03 ± 0.32
Intercept age	[1000	FUSE]						14.0 ± 0.2



A.3A



A.3B

Figure A.3  $^{40}\text{Ar}/^{39}\text{Ar}$  plots for sample 910077. A shows the  $^{40}\text{Ar}/^{39}\text{Ar}$  release spectrum and B shows an isochron plot for sample 910077.

**SAMPLE 910078**

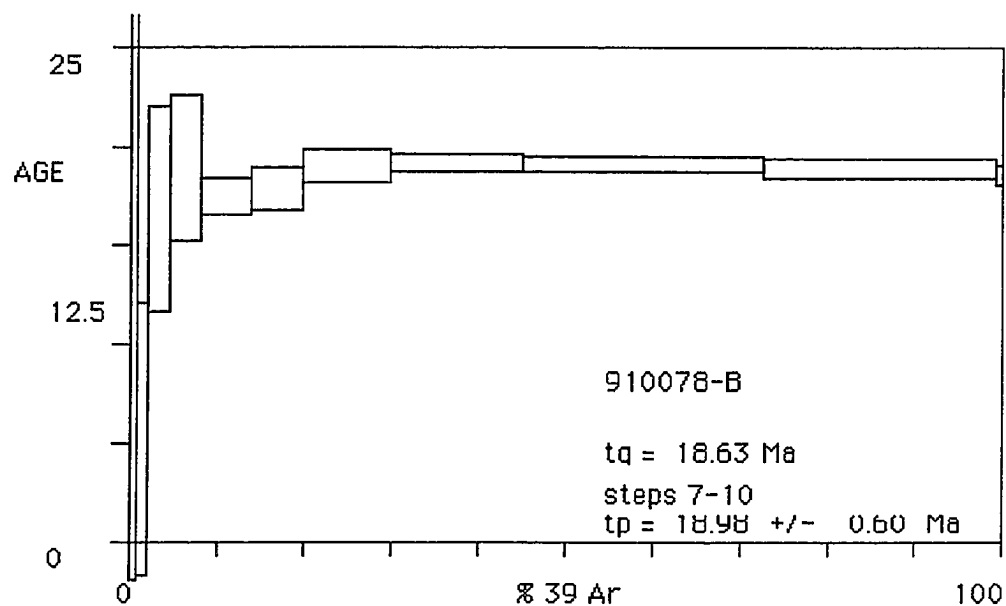
910078-B

$$J = .010327.$$

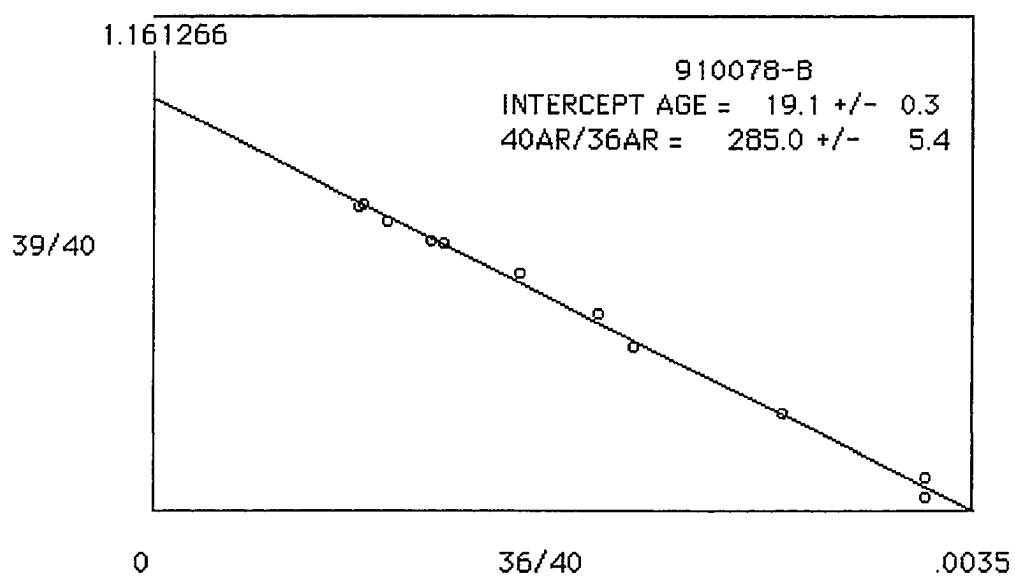
Biotite separate.

Table A.4  $^{40}\text{Ar}/^{39}\text{Ar}$  release data for sample 910078.

Temp (°C)	40/39	37/39	36/39	Moles 39	%Total	% Radiogenic	K/Ca	AGE (Ma)
750	34.485	0.347	0.1140	12.0	0.7	2.3	1.41	14.97 ± 16.85
840	12.562	0.177	0.0416	24.6	1.4	2.2	2.77	5.22 ± 6.92
930	4.462	0.089	0.120	43.2	2.4	20.4	5.53	16.86 ± 5.19
1000	2.607	0.064	0.0053	67.2	3.7	39.1	7.70	19.89 ± 3.70
1050	2.168	0.049	0.0041	101.7	5.6	43.5	10.01	17.49 ± 0.95
1100	1.809	0.042	0.0028	109.1	6.0	53.2	11.64	17.85 ± 1.11
1150	1.597	0.043	0.0019	183.5	10.1	64.4	11.42	19.06 ± 0.87
1200	1.486	0.041	0.0015	275.3	15.2	69.7	11.98	19.21 ± 0.43
1250	1.410	0.038	0.0012	500.7	27.6	73.3	12.99	19.15 ± 0.40
1300	1.403	0.030	0.0012	482.1	26.6	72.8	16.16	18.93 ± 0.48
FUSE	1.599	0.027	.00020	14.6	0.8	62.7	17.90	18.58 ± 0.51
Total				1814.1	100.0			18.63 ± .98
Plateau age	(1150	1300)						19.08 ± 0.34
Intercept age								19.1 ± 0.3



A.4A



A.4B

Figure A.4  $^{40}\text{Ar}/^{39}\text{Ar}$  plots for sample 910078. A shows the  $^{40}\text{Ar}/^{39}\text{Ar}$  release spectrum and B shows an isochron plot for sample 910078.

**SAMPLE 910079**

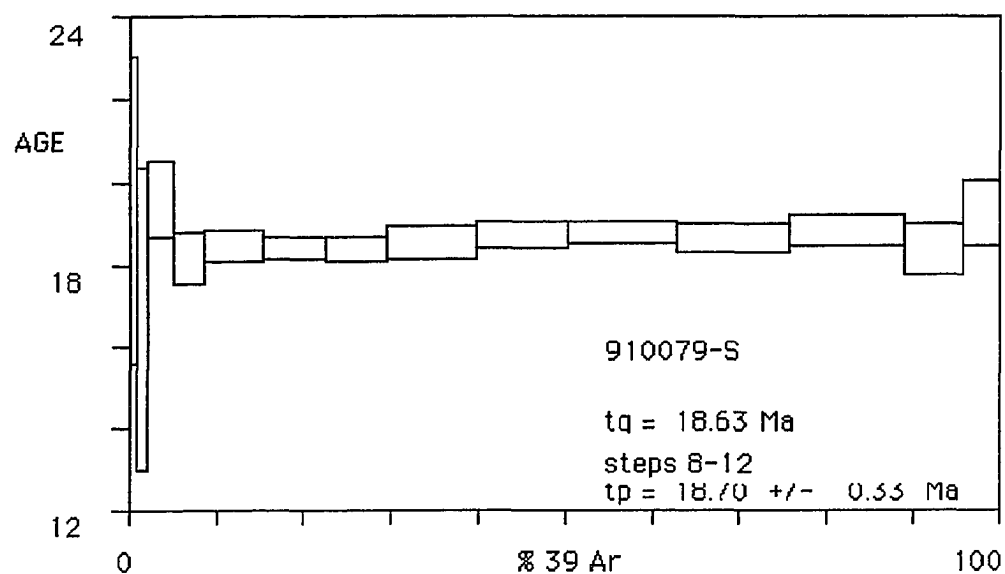
910079-S

J = .010385.

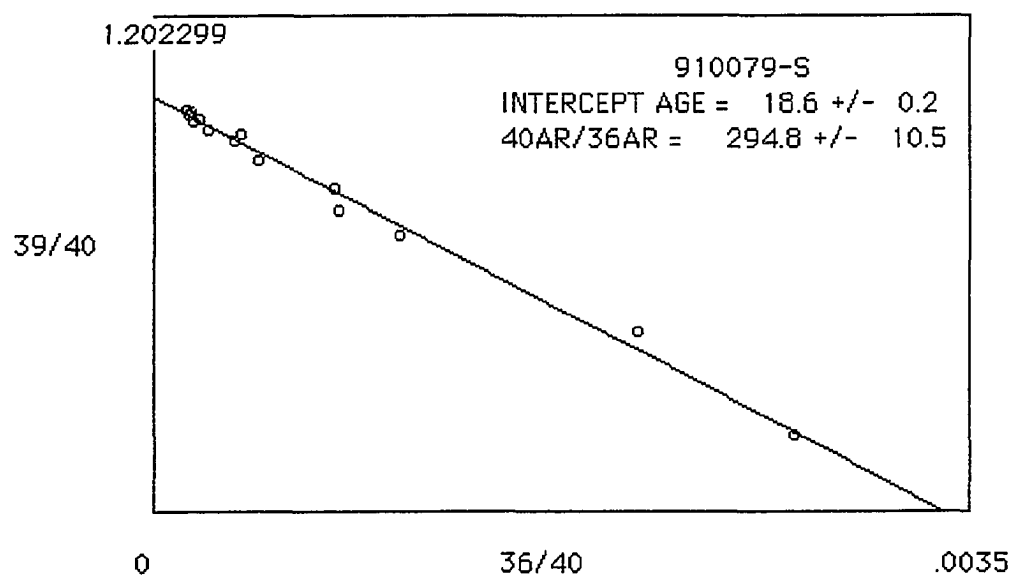
Sanidine separate.

Table A.5  $^{40}\text{Ar}/^{39}\text{Ar}$  release data for sample 910079.

Temp (°C)	40/39	37/39	36/39	Moles 39	%Total	% Radiogenic	K/Ca	AGE (Ma)
810	5.533	0.071	0.0152	38.6	0.8	18.7	6.92	19.33 ± 3.74
890	2.316	0.047	0.0048	65.2	1.3	38.6	10.48	16.68 ± 3.69
955	1.389	0.033	0.0011	147.6	3.0	75.8	14.95	19.61 ± 0.93
1015	1.111	0.028	0.0004	177.6	3.6	87.6	17.73	18.15 ± .62
1070	1.067	0.026	0.0002	330.5	6.6	92.7	18.60	18.44 ± 0.36
1125	1.052	0.024	0.0002	355.8	7.1	94.0	20.33	18.42 ± 0.27
1175	1.045	0.023	0.0002	351.1	7.1	94.3	21.45	18.37 ± 0.30
1220	1.057	0.022	0.0002	510.1	10.2	94.1	22.28	18.53 ± 0.41
1265	1.073	0.022	0.0002	524.7	10.5	93.6	22.51	18.72 ± 0.34
1305	1.098	0.021	0.0003	620.4	12.5	91.8	23.17	18.79 ± 0.26
1345	1.131	0.021	0.0004	655.7	13.2	88.5	23.29	18.65 ± 0.37
1385	1.189	0.021	0.0006	654.4	13.1	84.9	23.61	18.82 ± 0.38
1410	1.294	0.021	0.0010	340.5	6.8	76.1	22.91	18.36 ± 0.60
FUSE	1.515	0.021	0.0016	206.2	4.1	68.2	23.52	19.26 ± 0.79
Total				4978.2	100.0			18.63 ± 0.47
Plateau age	[1220	1385]						18.70 ± 0.33
Isochron age	[1220	1385]						18.6 ± 0.2



A.5A



A.5B

Figure A.5  $^{40}\text{Ar}/^{39}\text{Ar}$  plots for sample 910079. A shows the  $^{40}\text{Ar}/^{39}\text{Ar}$  release spectrum and B shows an isochron plot for sample 910079.



**SAMPLE 910080**

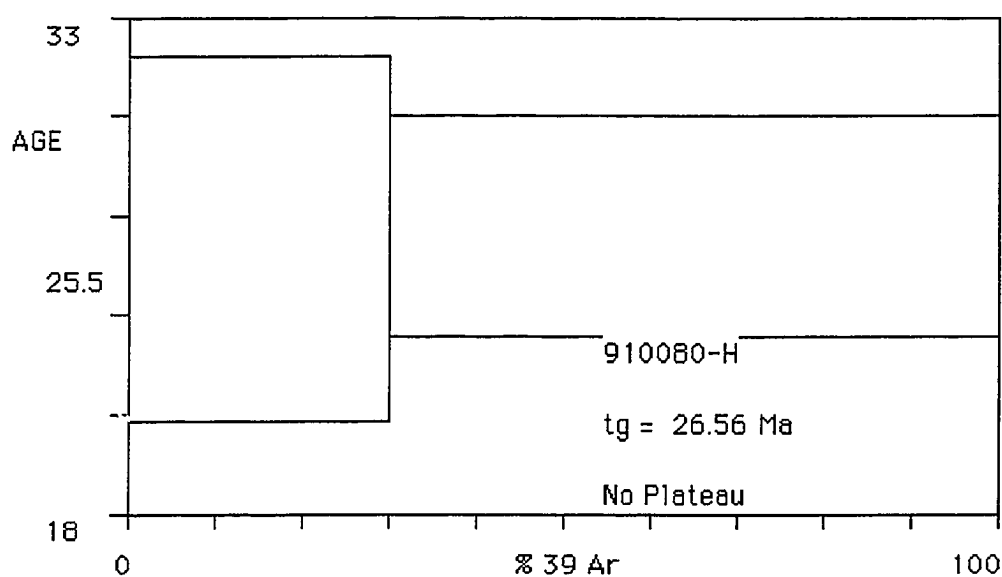
910080-H

$$J = .010395.$$

Hornblende separate.

Table A.6  $^{40}\text{Ar}/^{39}\text{Ar}$  release data for sample 910080.

Temp (°C)	40/39	37/39	36/39	Moles 39	%Total	% Radiogenic	K/Ca	AGE (Ma)
FUSE spl1	10.00	4.8845	0.0304	39.2	29.9	14.1	0.100	$26.30 \pm 5.53$
FUSE spl2	10.15	4.8804	0.0308	91.8	70.1	14.1	0.100	$26.67 \pm 3.36$
Total				131.0	100.0			$26.56 \pm 4.01$

Figure A.6  $^{40}\text{Ar}/^{39}\text{Ar}$  release spectrum for sample 910080.

## **APPENDIX B - LOCATION OF PALEOMAGNETIC, ISOTOPIC AND FOSSIL SITES IN THE SOUTHWEST CADY MOUNTAINS**

### **INTRODUCTION**

Rocks were sampled for paleomagnetic and isotopic analysis throughout the southwest Cady Mountains. All of the stratigraphic units (formation of Poe, formation of Troy Peak, and "Barstow Formation") were sampled for paleomagnetic analysis during the spring of 1990. Preliminary analysis of these samples showed that certain lithologies gave more consistent and stable results. Units sampled in 1991 were chosen based on the data gathered from the 1990 samples.

Rocks sampled for isotopic analysis were obtained in 1991. The isotopic sites are located at certain paleomagnetic sites, with the exception of site 910075, which is at the base of the formation of Poe section immediately south of paleomagnetic site 9008.

Table B.1, on the next page, gives a summary of the locations of each of these sites. Figure B.1 shows the general location of each of these sites with expanded views of two areas of concentrated sampling area are shown in Figure B.2. One paleomagnetic site (9128) and one isotopic site (Samples 910078 and 910079) are not located in Figure B.1. These sites occupy the same location listed in Table B.1 and are designated on Plate 1.

Table B.1 Paleomagnetic, isotopic and fossil sample locations.

Site	Location Lat/Long	Site	Location Lat/Long
<b>Paleomagnetic</b>	<b>Sites</b>	<b>Fossil</b>	<b>Locality</b>
9007	34.842/-116.527	RV-9001	34.825/-116.503
9009	34.841/-116.530		
9014	34.842/-116.530		
9015	34.842/-116.530		
9018	34.843/-116.532		
9019	34.843/-116.533		
9020/21	34.844/-116.534		
9024	34.844/-116.522		
9026	34.822/-116.497		
9027	34.822/-116.497		
9029	34.820/-116.500		
9030	34.820/-116.500		
9031	34.817/-116.500		
9033	34.848/-116.531		
9034	34.848/-116.531		
9035	34.848/-116.531		
9036	34.848/-116.531		
9037	34.848/-116.530		
9038	34.849/-116.530		
9102	34.831/-116.548		
9103	34.825/-116.504		
9104	34.825/-116.504		
9105	34.825/-116.503		
9108	34.825/-116.503		
9112	34.822/-116.497		
9113	34.822/-116.498		
9114	34.841/-116.530		
9115	34.842/-116.530		
9117	34.821/-116.501		
9118	34.821/-116.501		
9119	34.821/-116.501		
9120	34.819/-116.499		
9121	34.817/-116.500		
9123	34.842/-116.531		
9124	34.843/-116.532		
9125	34.847/-116.530		
9126	34.813/-116.503		
9127	34.812/-116.502		
9129	34.841/-116.528		

<b>Isotopic</b>	<b>Sites</b>
910075	34.840/-116.530
910076	34.812/-116.502
910077	34.820/-116.500
910078	34.872/-116.478
910079	34.872/-116.478
910080	34.832/-118.552

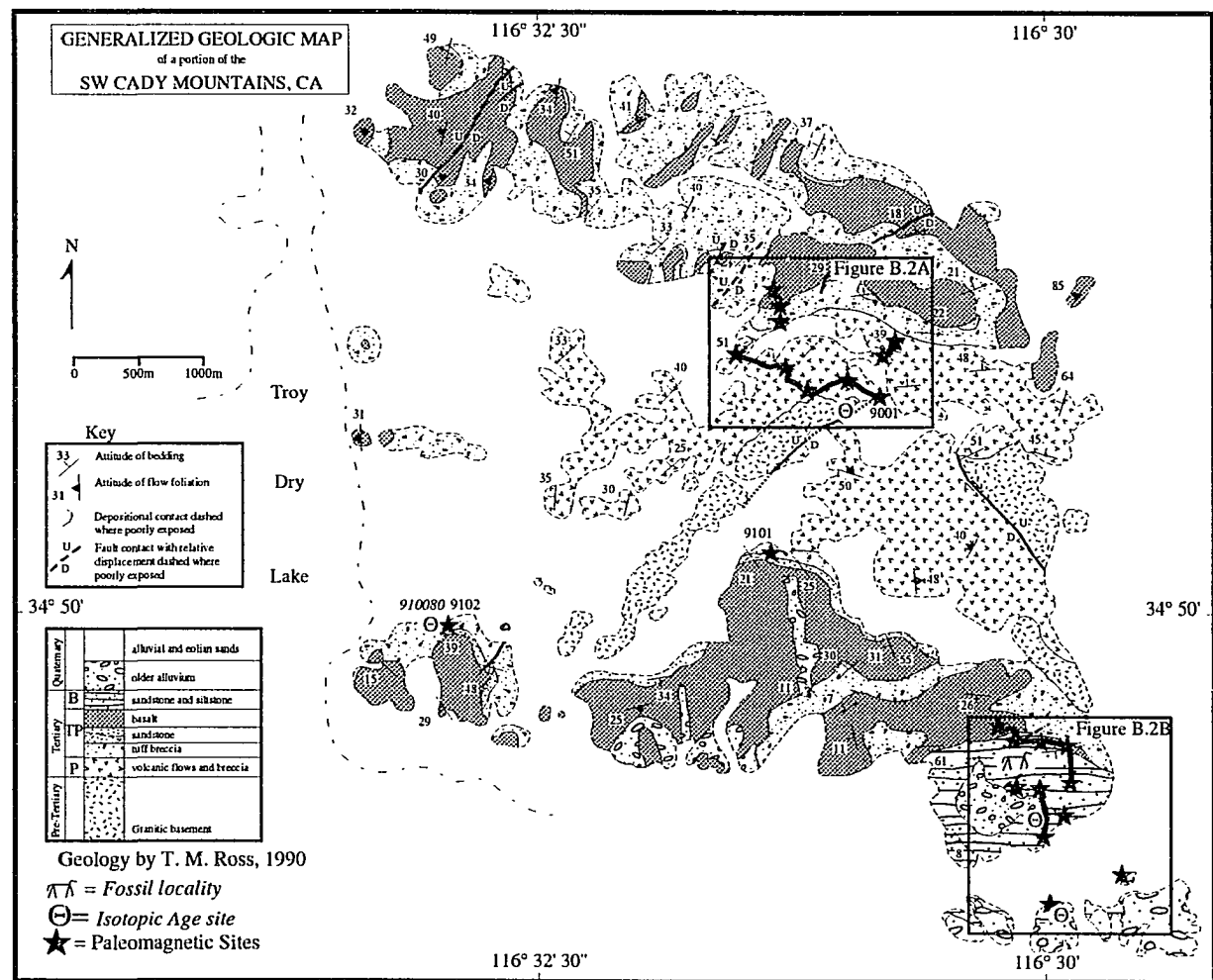
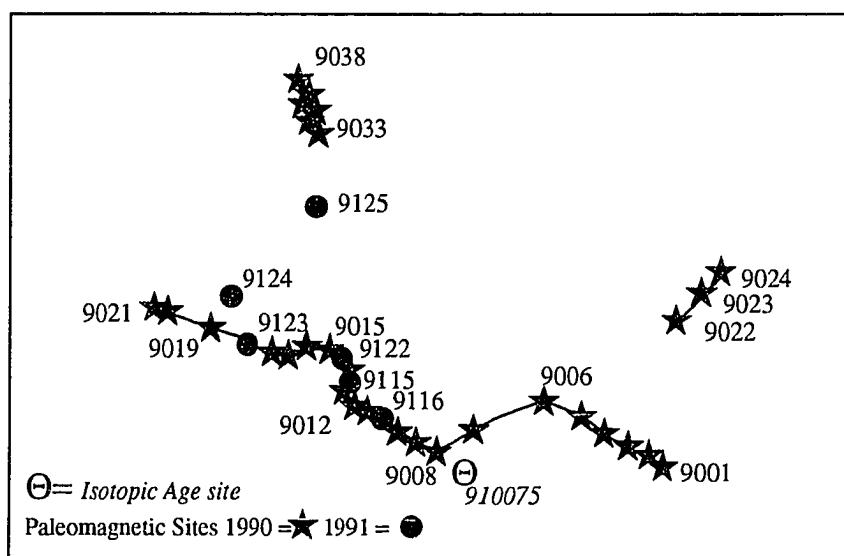
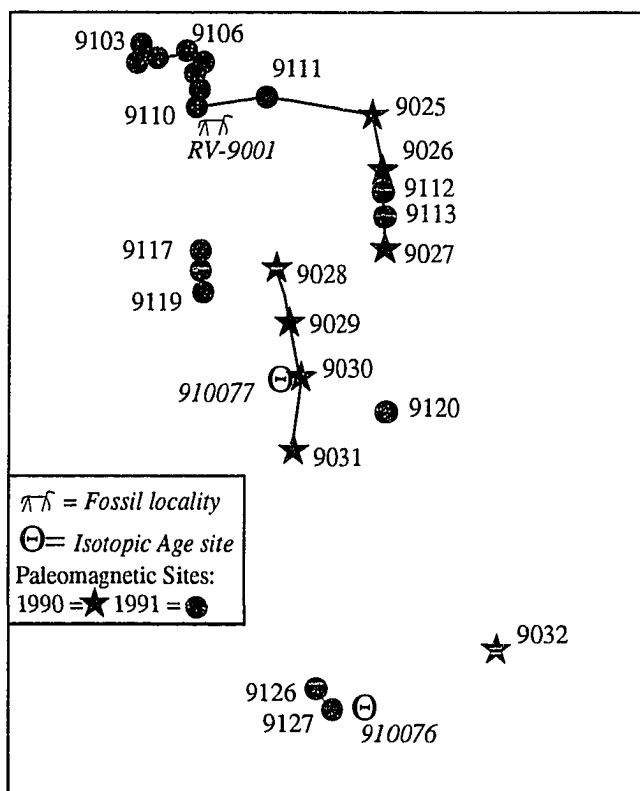


Figure B.1 Location of fossil, paleomagnetic and isotopic sites.



B.2B



**Figure B.2** Sample localities in the central and southeastern study area. A shows localities in the central area, whereas B shows those in the northeastern area. These areas are shown on figure B.1.

## VITA

Timothy Michael Ross was born August 18, 1961 to Zannie Lynn Ross (née Dixon) and James Douglas Ross in Bakersfield, California. He completed his public elementary and secondary education in Fresno, California, receiving his diploma for Herbert Hoover High School in June, 1980. Mr. Ross earned his Bachelor of Science degree in Geology from California State University, Fresno in 1985. He completed a Master of Arts degree in Geology from the University of California, Santa Barbara in 1988, where he began his interest in the geology of the Mojave Desert. During his Master's studies he worked with Dr. Bruce P. Luyendyk, Dr. Michael D. Fuller, and Dr. Richard H. Sibson.

Mr. Ross embarked on his Doctoral studies in August, 1988 at Louisiana State University, Baton Rouge, where he was honored with a Board of Regents Doctoral Fellowship. During this adventure he learned much about geology and life from his advisor, Dr. Roy K. Dokka, his committee members, and his fellow graduate students. He completed this endeavor in the fall of 1993. Mr. Ross married Dr. Joan Esther Fryxell in September, 1992. They have a son.

**DOCTORAL EXAMINATION AND DISSERTATION REPORT**


**Candidate:** Timothy Michael Ross

**Major Field:** Geology

**Title of Dissertation:**

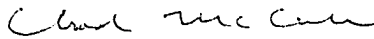
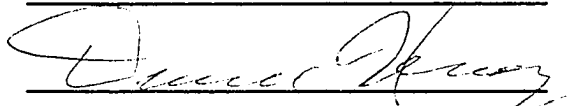
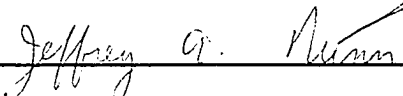
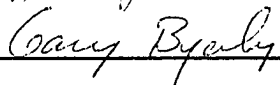
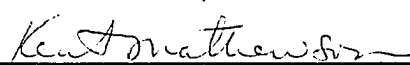
Neogene Extension and Regional Rotation of the Central Mojave  
Desert, California

**Approved:**

  
\_\_\_\_\_  
Major Professor and Chairman

  
\_\_\_\_\_  
Dean of the Graduate School

**EXAMINING COMMITTEE:**

  
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**Date of Examination:**

September 13, 1993

**PLEASE NOTE:**

Oversize maps and charts are filmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

**University Microfilms International**





116° 32' 30"

unmapped

A

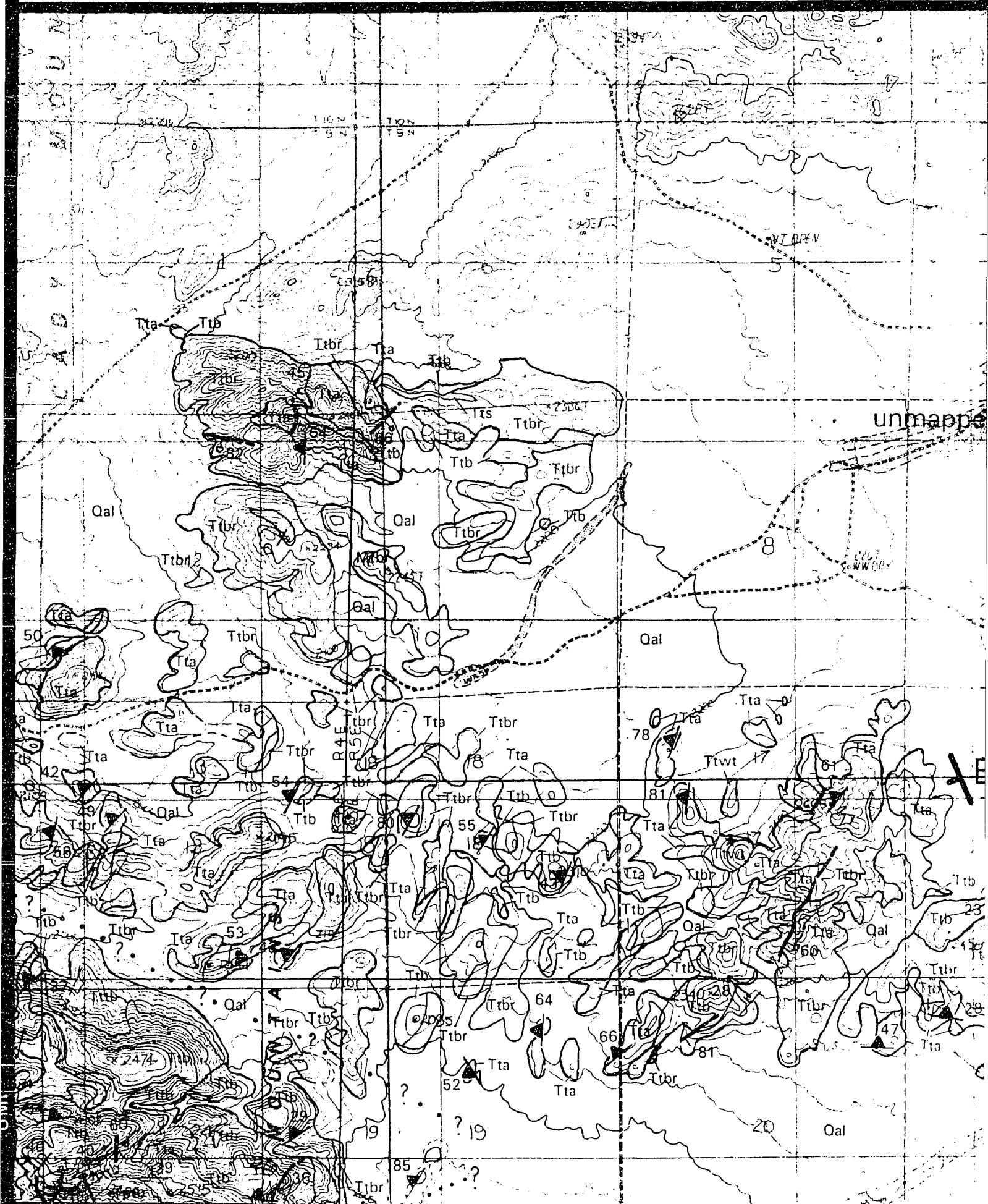
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34° 52' 30" 16

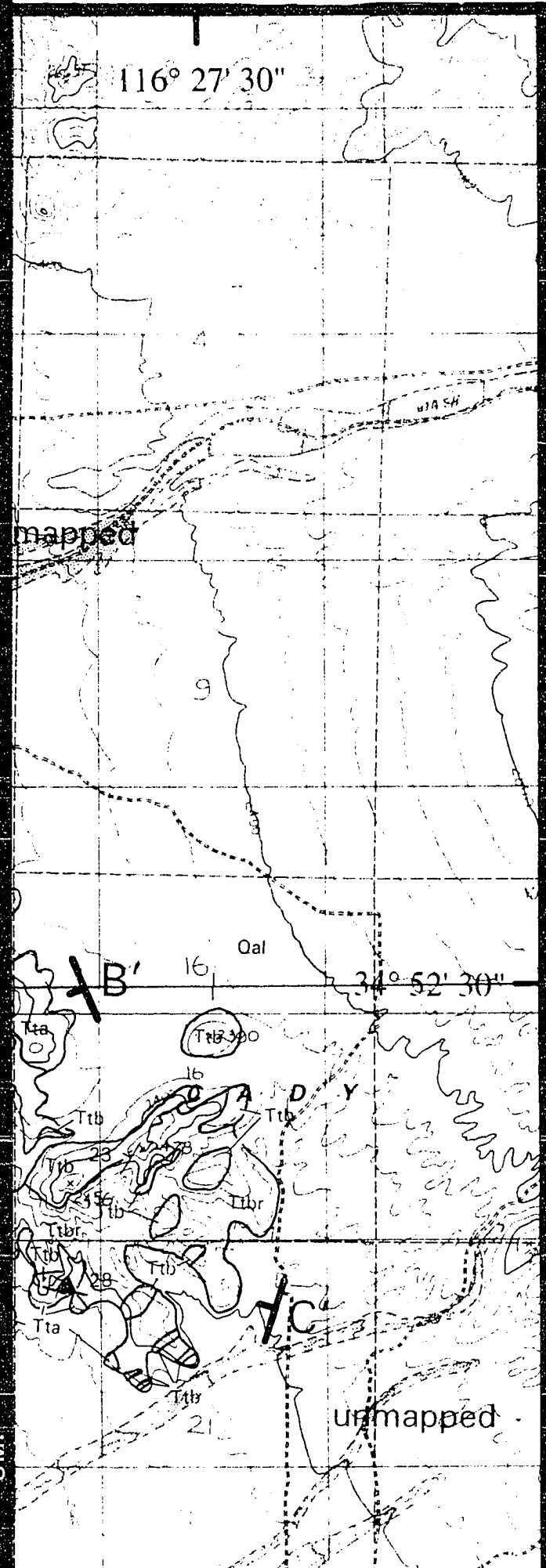
unmapped

DRY  
LAKE

DRY  
LAKE



# Geologic map of the south San Bernardino by Timothy Louisiana S



## Explanation:

Stratigraphy: (order of units within informal formations does not indicate stratigraphic succession)

Quaternary { 

Q	Qal	Qlg
---	-----	-----

  
Q - Quaternary undifferentiated  
Qal - active to recent alluvial deposits  
Qlg - older conglomerate deposits  
*unconformity*

middle Miocene { 

Tbs	Tbb
-----	-----

 "Barstow Formation"  
Tbs - sandstones and siltstones  
Tbb - conglomerates and breccias  
*unconformity*

lower Miocene { 

Tta	Ttb	Tts	Tttb	Ttr	Ttrw
-----	-----	-----	------	-----	------

 Formation  
Tta - andesitic lava flows  
Ttb - basaltic lava flows  
Tts - tuftaceous sandstones (new)  
Tttb - distinctive monolithologic tuff  
Ttr - multilithologic tuff breccia  
Ttrw - welded sandstone rich tuff  
*unconformity*

upper Oligocene (?) / lower Miocene { 

Tpa	Tpb	Tpt	Tptb
-----	-----	-----	------

 Formation of P  
Tpa - andesite flows  
Tpb - basaltic flows  
Tpt - lapilli tuff  
Tptb - tuff breccia  
*unconformity*

pre-Tertiary { 

g
---

  
g - granite and quartz monzonite

# Plate 1

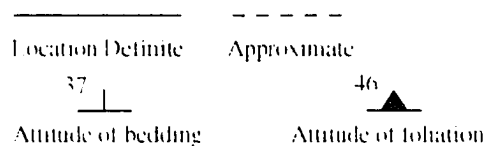
## The southwest Cady Mountains, Sardinia County, California

Timothy M. Ross

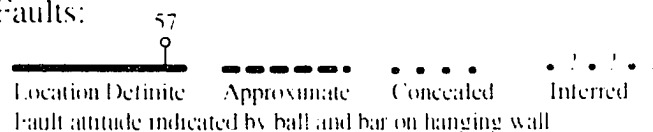
Idaho State University

### Symbols:

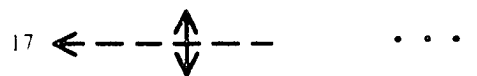
#### Depositional Contacts:



#### Faults:



#### Folds:



Approximate Axial Trace of Antiform    Concealed and Inferred

#### Other Symbols:

X † † X † Location of cross section lines

• • • Fossil locality

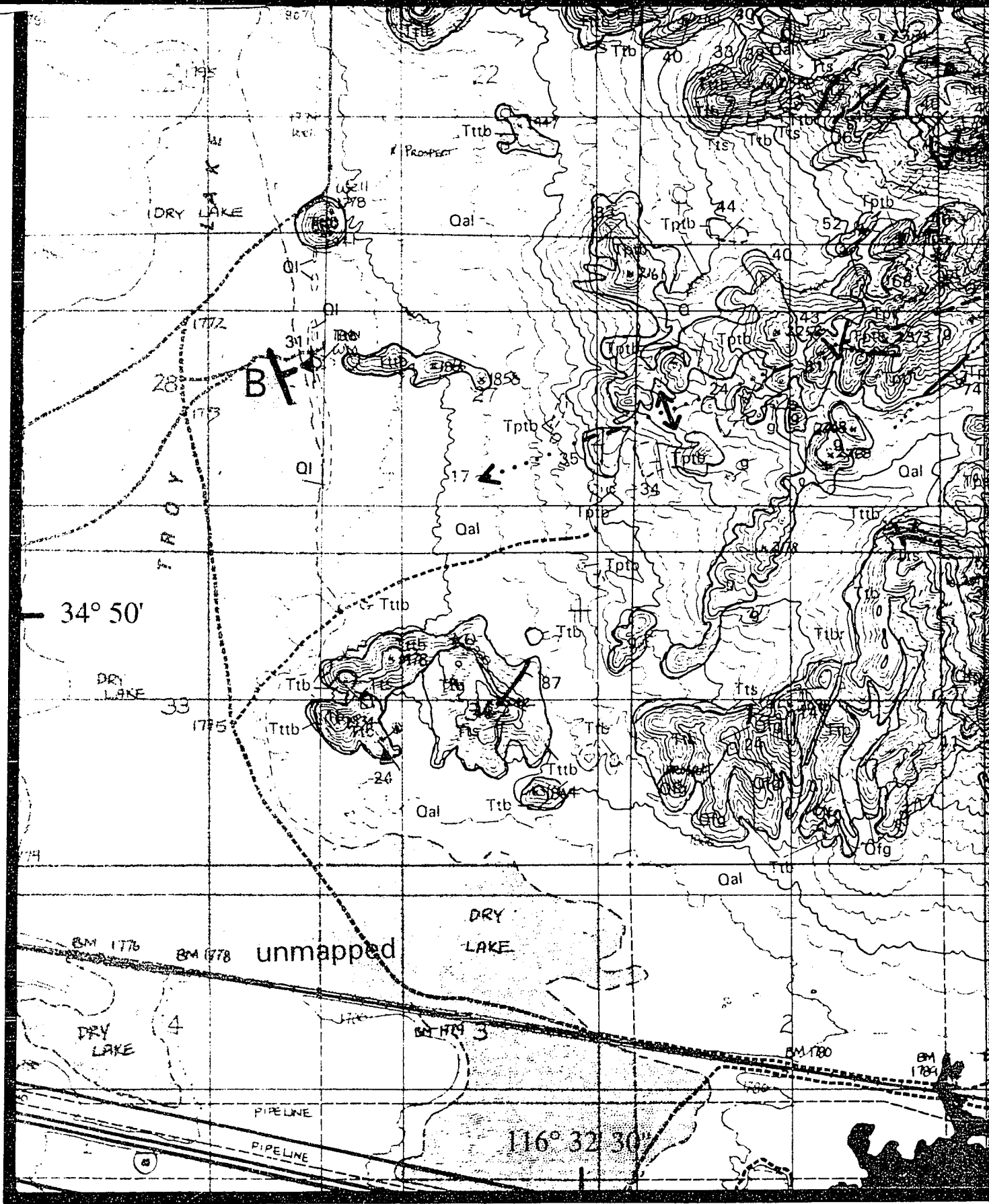
★ Paleomagnetic site

⊖ Isotopic Age site

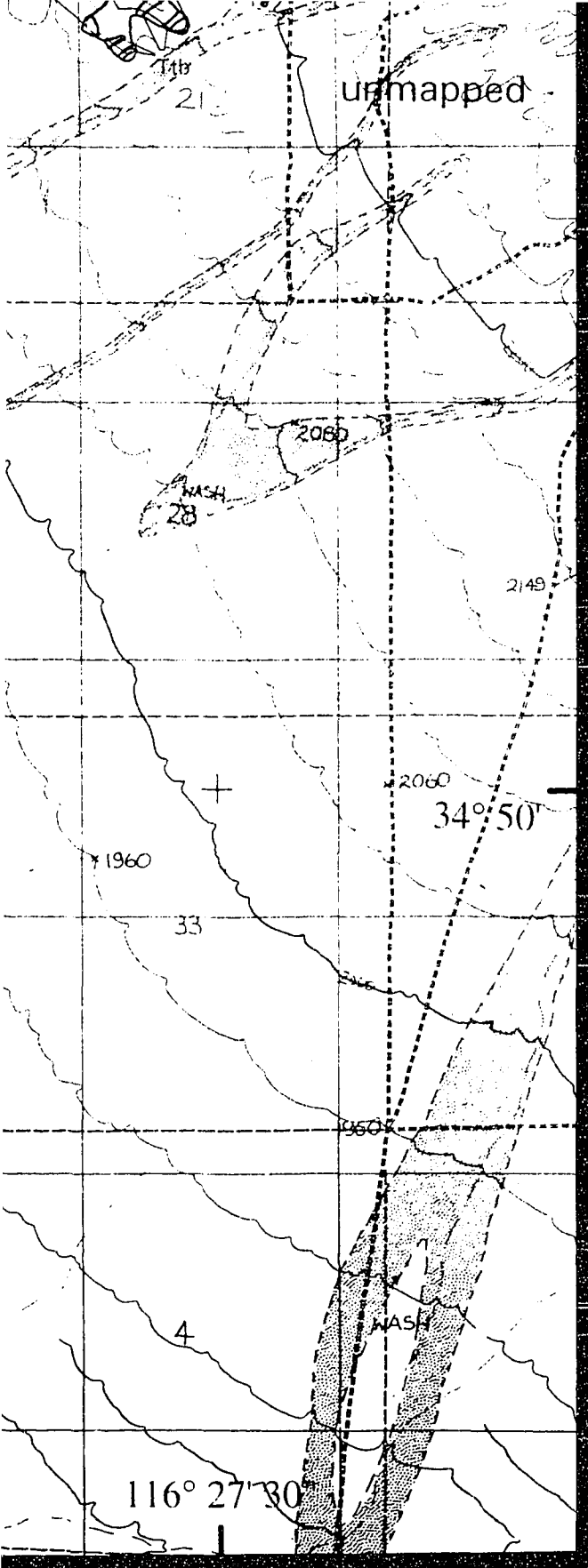
} site numbers given  
in Appendix B

Geology mapped at 1:12,000 in 1989, 1990, 1991

Topographic base produced from the NE portion of the Troy Lake, the SE portion of the Manix, the SW portion of the Hidden Valley West, and the NW portion of the Hector U.S.G.S. 7.5' Quadrangles. Contour interval is 40' for the Hidden Valley West and Hector Quadrangles, and 20' for the Manix and Troy Lake Quadrangles.

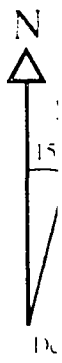
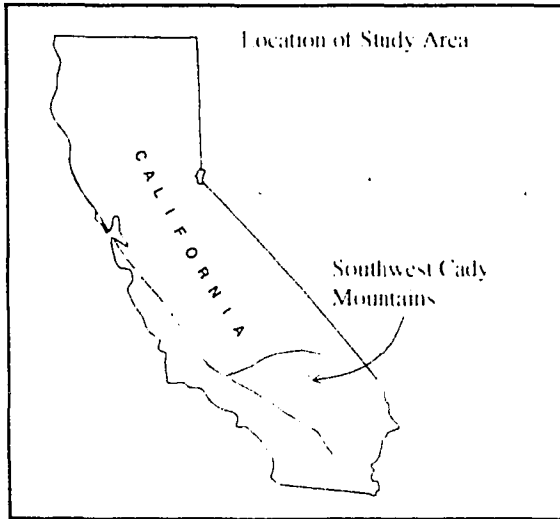






pre-Tertiary { g

unconformity  
g - granite and quartz monzonite





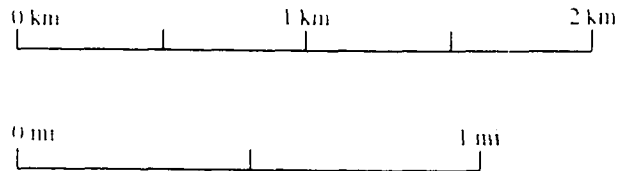
01b - tuff breccia  
unconformity  
granite and quartz monzonite

vicinity mapped at 1:12,000 in 1989, 1990, 1991  
Topographic base produced from the NE portion of the Troy Lake,  
the SE portion of the Mamix, the SW portion of the Hidden Valley  
West, and the NW portion of the Hector U.S.G.S. 7.5' Quadrangles.  
Contour interval is 40' for the Hidden Valley West and Hector  
Quadrangles, and 20' for the Mamix and Troy Lake Quadrangles.



Declination 15 E.

Scale 1:24,000



**PLEASE NOTE:**

Oversize maps and charts are filmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

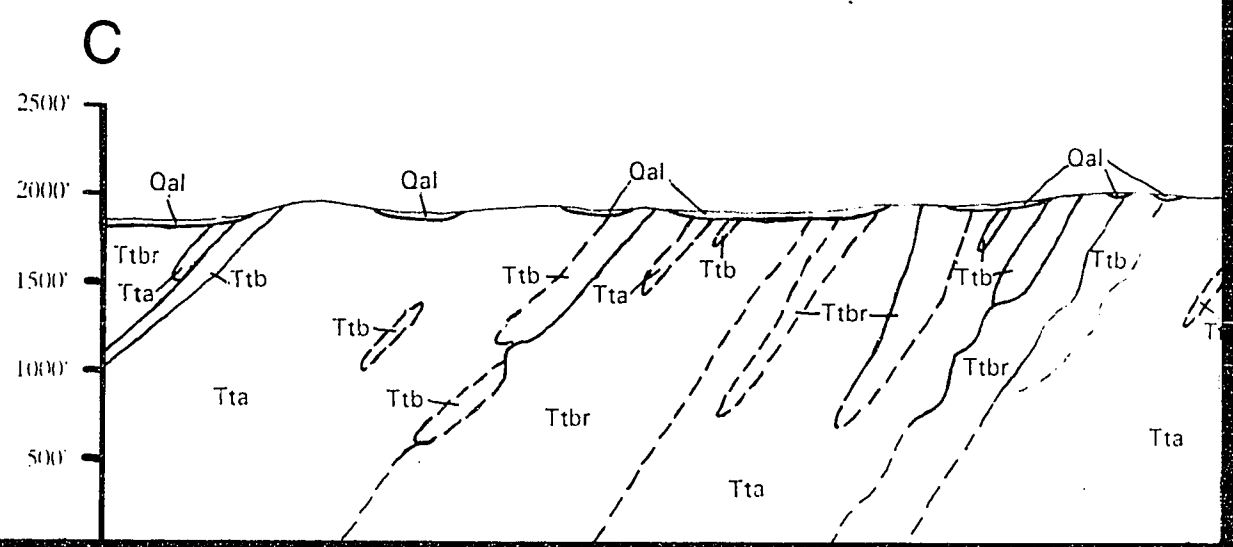
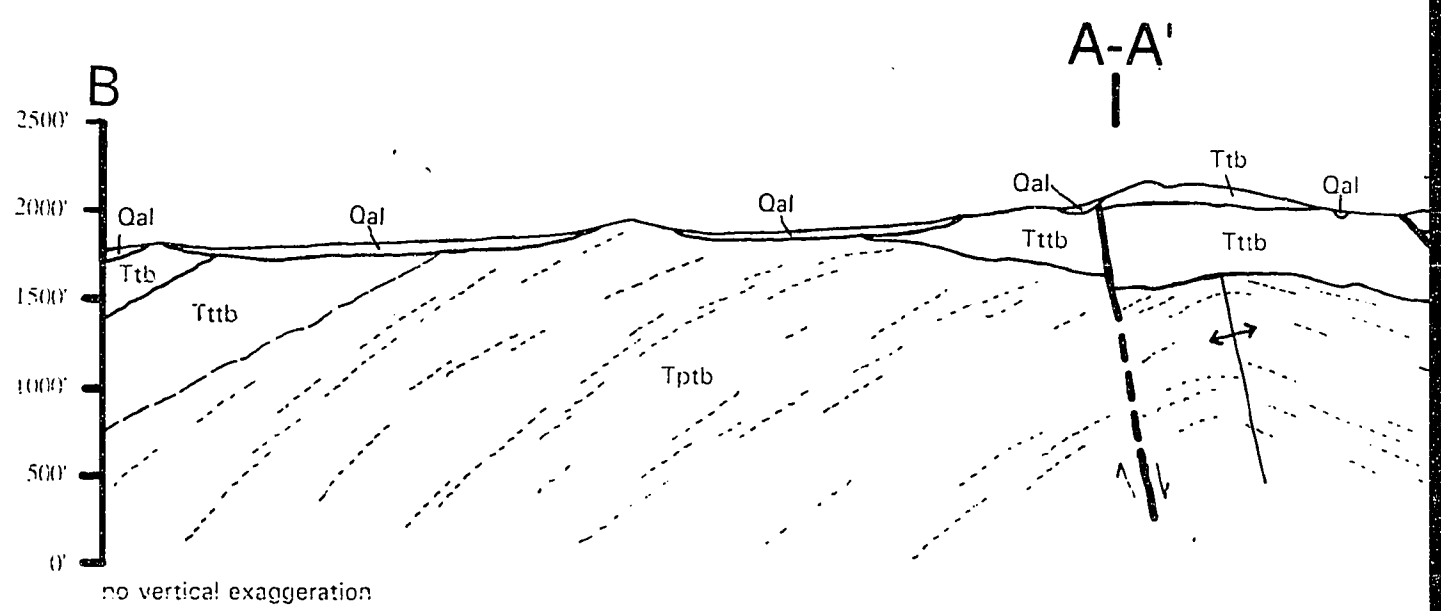
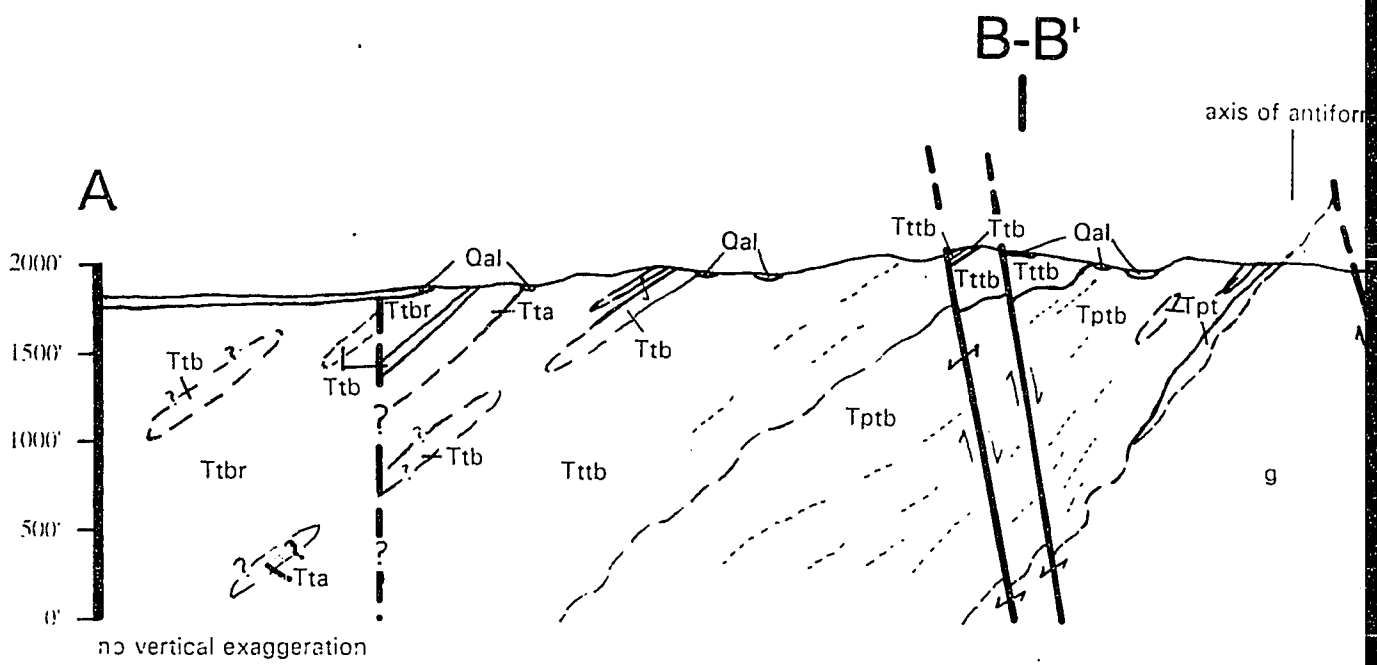
Black and white photographic prints (17" x 23") are available for an additional charge.

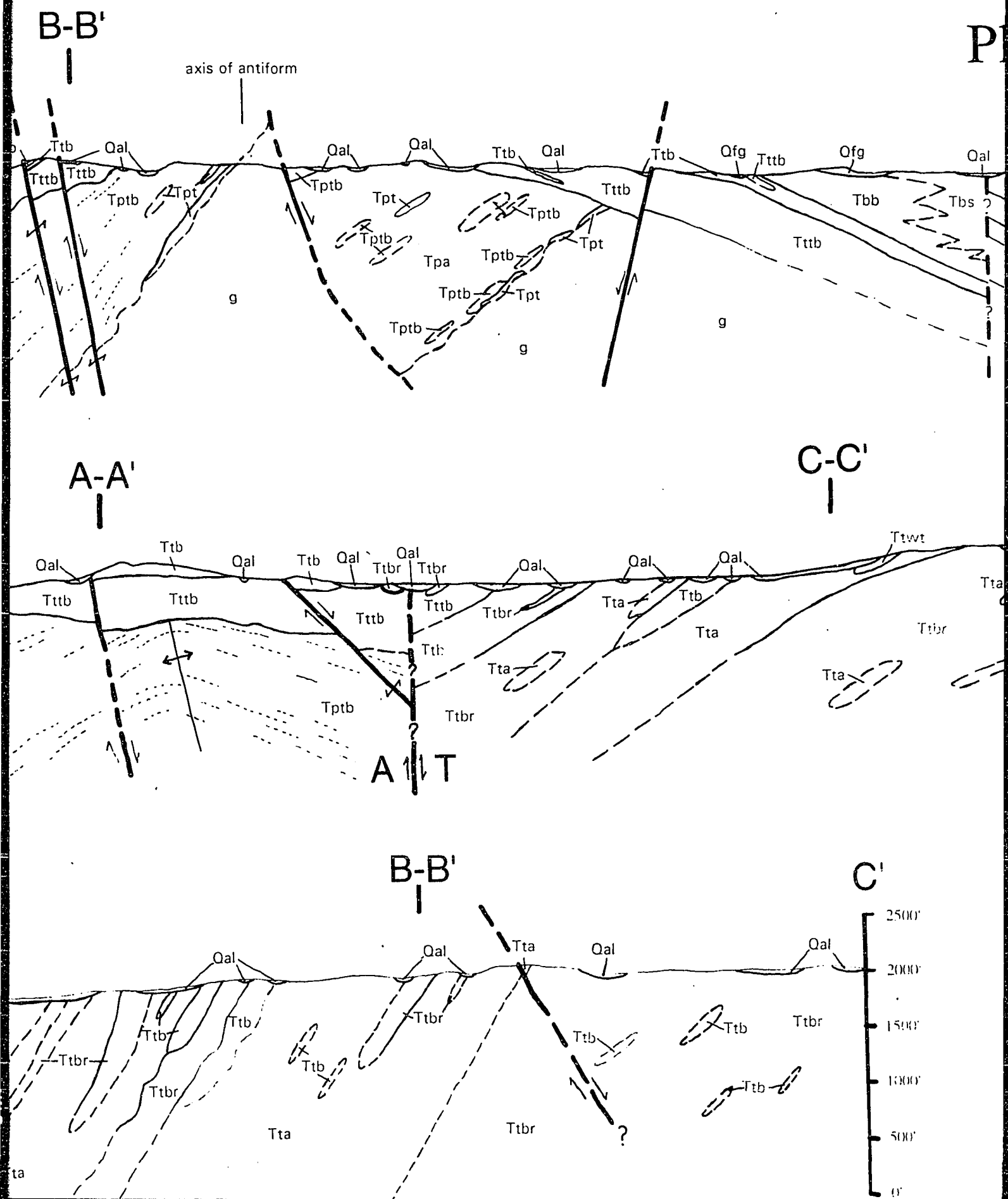
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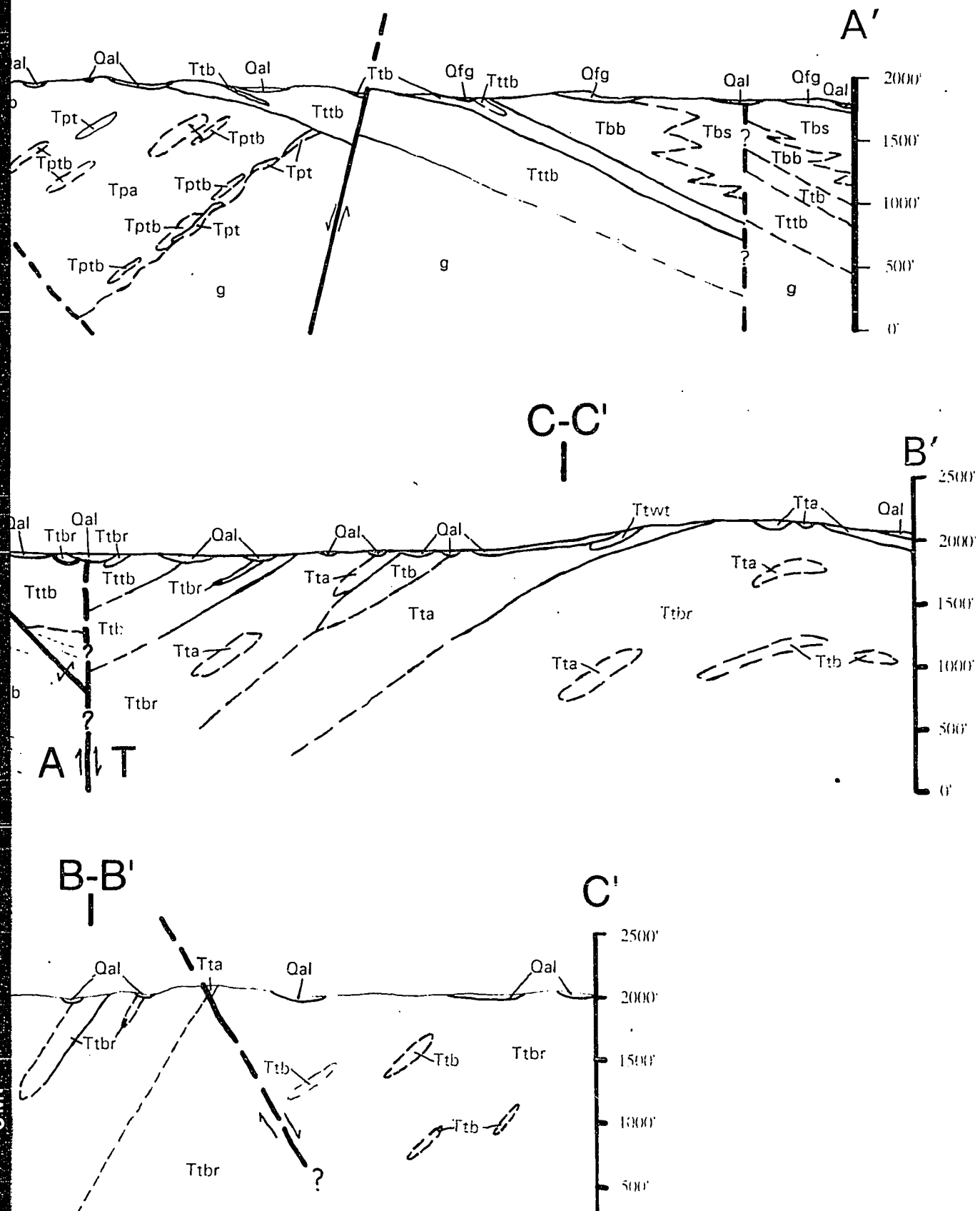
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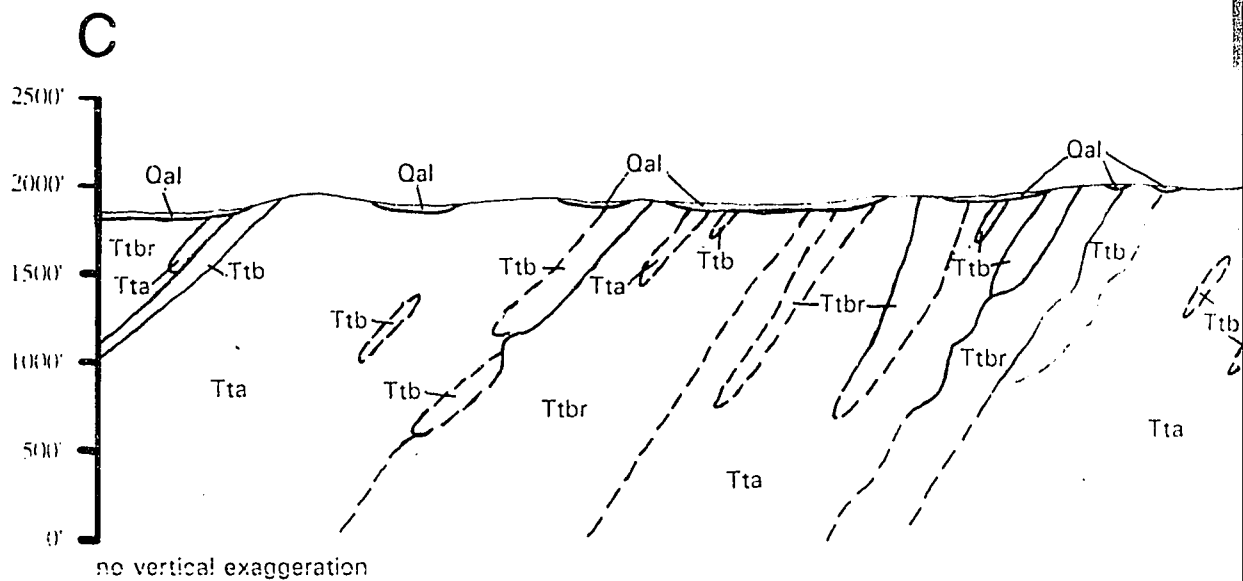
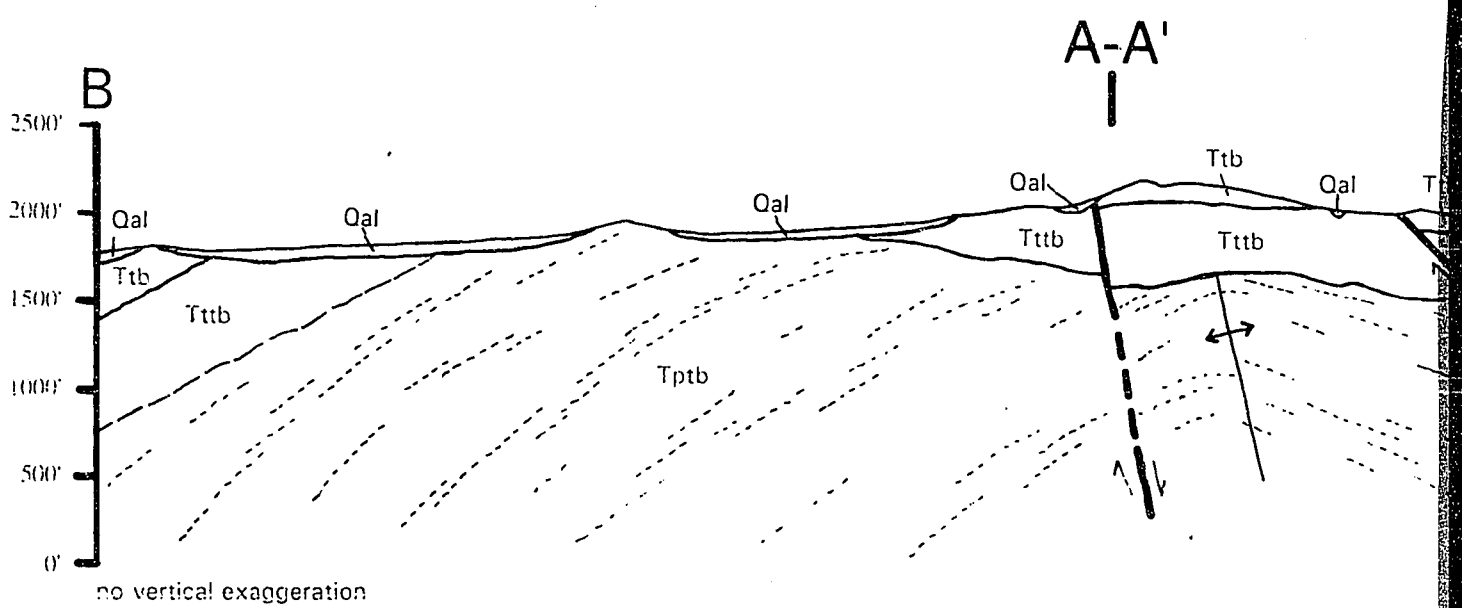




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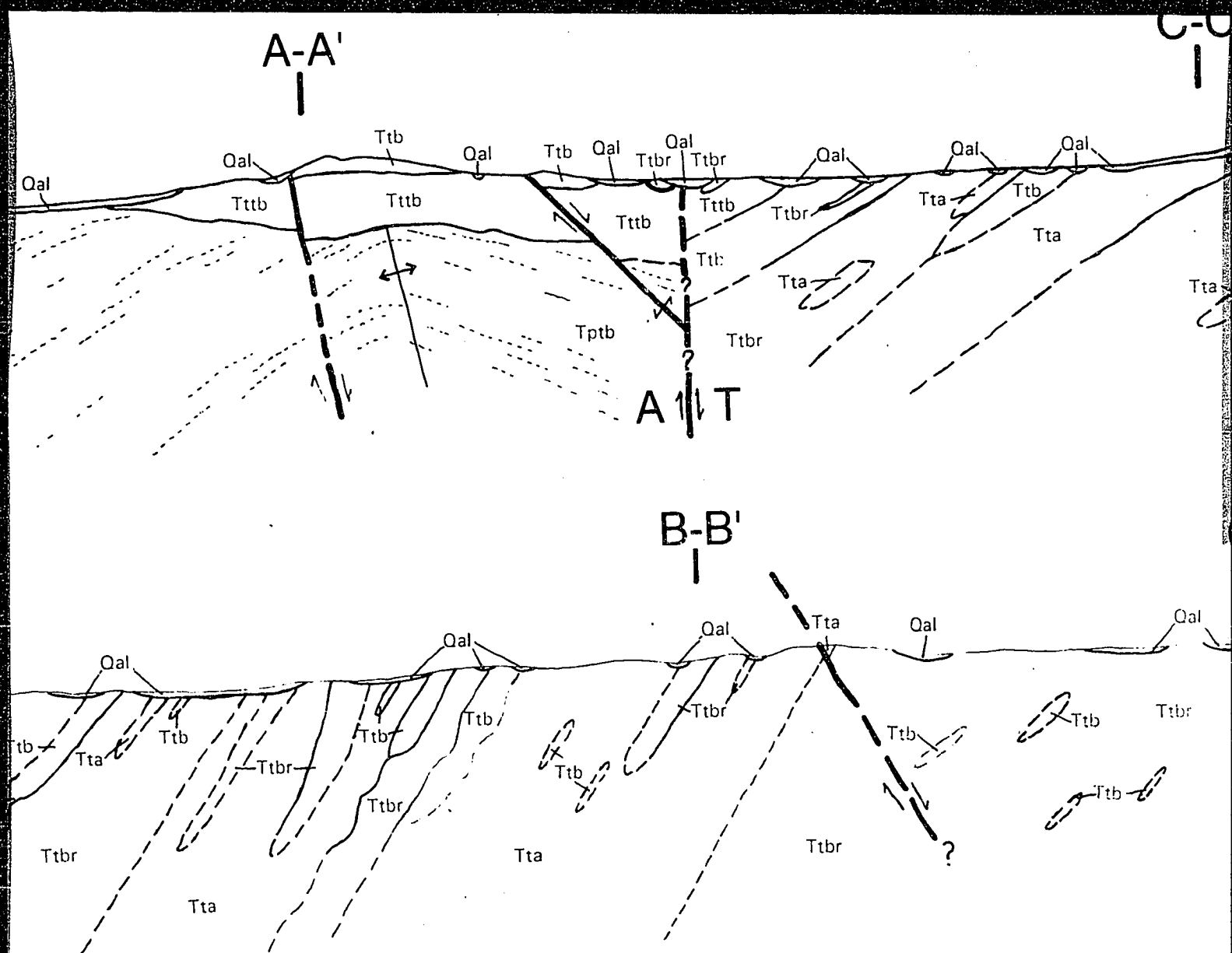
# Plate 2





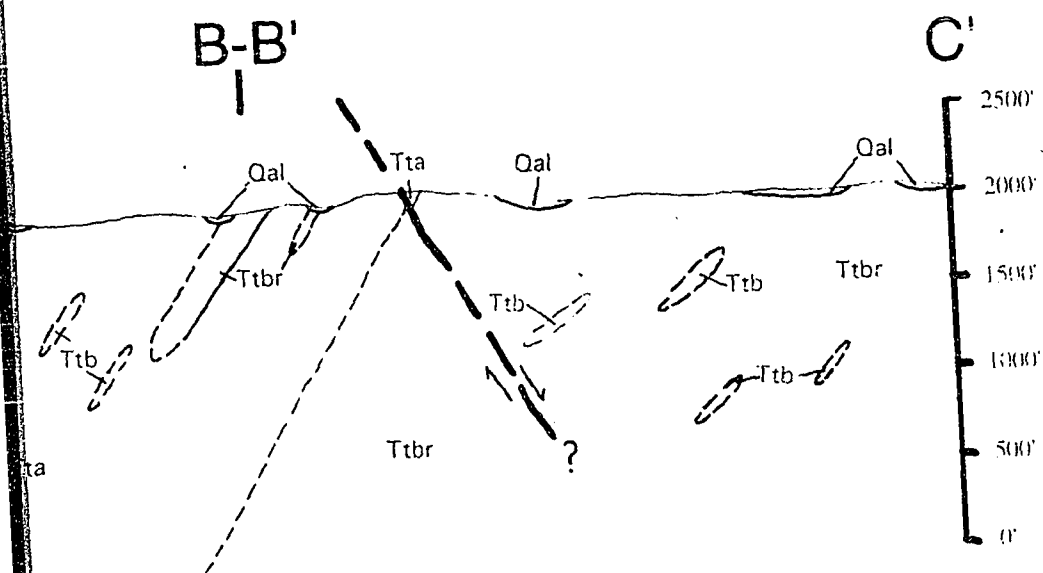
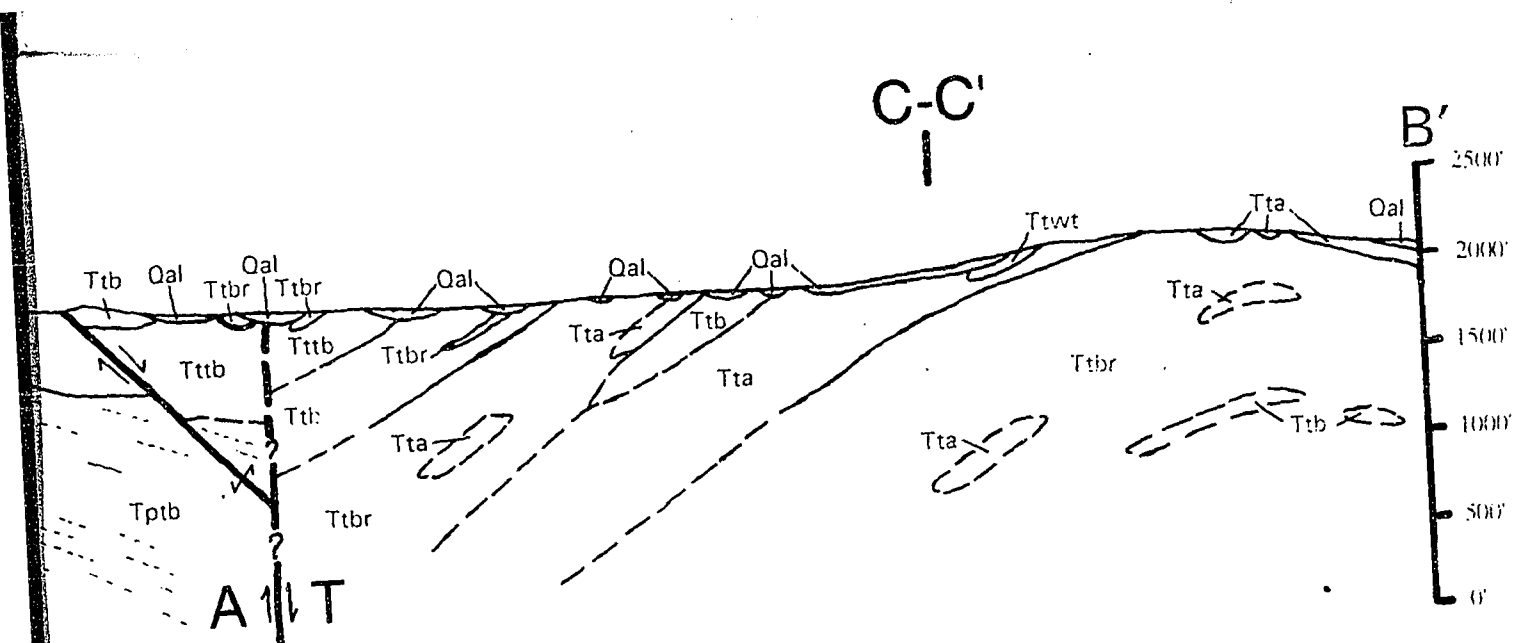
# Cross-Sections from the Southwest Ca

## by Timothy M. Ross



# from the Southwest Cady Mountains CROSS





# Cady Mountains